S. Venetsky

From the CAMP FIRE to the PLASMA

Mir Publishers Moscow

From the Camp Fire to the Plasma

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Сергей Венецкий

ОТ КОСТРА ДО ПЛАЗМЫ

Рассказ о многовековом пути, пройденном металлургией, — о поисках и находках, загадках и тайнах, идеях и свершениях

Издательство «Знание» Москва

S. Venetsky

From the CAMP FIRE to the PLASMA

A Story of the Many-Century Road Travelled by
Metallurgy, Quests and Finds, Riddles and
Mysteries, Ideas and Accomplishments

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Foreword

There have been, in the history of civilization, important milestones without which it would be impossible to reconstruct the road travelled by mankind in its development. A long, long way back, perhaps many thousand years ago, our forefathers learned how to obtain fire. Then man learned how to raise livestock, to grow cereals and, in making another big leap forward, how to turn ores into metals.

The mastery of metallurgy, the art of extracting, smelting, and working metals, has been a significant landmark in man's biography, probably standing on a par with the taming of fire and the advent of livestock breeding and farming. It is metallurgy, which came into being, as archaeological excavations witness, somewhere in the seventh millenium before our times and falls therefore among the most ancient fields of man's endeavour, that gave powerful impetus to the growth of productive forces and supplied man with the metals vitally essential for the growth of material culture. It is no coincidence that the key periods in man's history are now referred to by the name of the metal predominant at a particular time, such as the Copper Age, the Bronze Age, and the Iron Age.

Since it became a fact of life, metallurgy has until now travelled a long, eventful and intriguing road from the charcoal of camp fires and simple hearths in which ores were turned, at the dawn of civilization, into balls of metal, to present-day mammoth iron and steel plants where the traditional fuel-fired furnaces are operating hand in hand with huge electroslag, electron-beam and plasma units in making high-quality metals.

This road many centuries long is described in the book you have in front of you. As I believe, it will not leave indifferent any reader, whatever his age may be. Of course, in a small book like this, it would have been hardly possible to draw a complete and all-round picture of the birth, growth and prospects of so multi-faceted an art and science as metallurgy is today. Nor, I think, has the author strived to do this. Drawing upon a veritable wealth of material related to the subject, he has been able to piece together a good many interesting and important events into an entertaining story of metal making in general, the early metal-making furnaces and processes, the many-century experience so often blazed with scientific thought, and daring ideas and projects aimed into the future. In a happy way, the author intertwines his story with facts from documents and scientific publications. Apart from letting the reader feel the spirit and colour of those days, the book offers an opportunity to look at the events through the eyes of those who have built the history of metallurgy.

The reader will have learned about millenia of quests and finds, major discoveries made by scientists and surprising feats performed by engineers, the plant and processes used or to be used to make metals in the past, present and future. Much as in actual life there has always been someone next to whatever it may be—the primitive hearth or the huge state-of-the-art blast furnace, so in the book the plant and processes are inseparable from those who have served the metal-making profession: P.P. Anosov, D.K. Chernov, H. Bessemer, P. Martin, M.K. Kurako, I.P. Bardin, and many others, both known and unknown metal-makers.

The book is not without some degree of bias—emphasis is placed on the contributions made by Soviet metallurgists. For one thing, they are less known to the reader outside the Soviet Union. For another, they too have won renown in metal-making practice throughout the world. Among the most important scientific and technological achievements that have been speeding up progress in metal-making, instrumentation, and other key fields of economy are various refining processes, powder and spray metallurgy, and direct reduction of ore. All of these highlights in Soviet and world metallurgical practice are covered in the book in particular detail.

Metallurgy in the 20th century bases itself on the latest advances in physics, chemistry, and physical chemistry. In turn, there are many spin-offs from metal-making: progress in these and, indeed, any other sciences would have been impossible without the various materials possessing a broad gamut of truly amazing properties, and these materials come from metallurgy, one of the most ancient, the most advanced, and the most promising of man's arts.

A.F. Belov,
Fellow, USSR Academy of
Sciences

Stone Loses Ground

(In Lieu of a Prologue)

Iron Hunger? — The "Pretty Messy" Picture — The Day and the Wink — Well Before Pithecanthropus — In the Jungle of New Guinea — From James Cook's Diary

In 1910, an International Geological Congress was held in Stockholm. Among the issues it was to deal with was iron hunger. An authoritative commission set up for the purpose turned in a balance sheet of the world's reserves of the metal. Top-ranking experts believed iron-ore deposits would completely be depleted in sixty years, that is, by 1970.

Fortunately enough, the savants have proved poor oracles, and even today man need not limit his iron consumption.

But what would happen, if the gloomy prediction had fulfilled and the iron ore deposits had been depleted? And, indeed, what would happen if all of iron vanished altogether and not a single gram of this element were left on our home planet?

"...The horror of destruction would then reign in the streets: no rails, no railway cars, no locomotives, no automobiles. Even the cobblestone would turn into clayish dust, and the plants would wither without this life-giving metal. As a hurricane, destruction would sweep the face of the Earth, and the death of mankind would be unavoidable".

This 'pretty messy' picture is drawn by A.E. Fersman, Fellow of the USSR Academy of Sciences, in his book in order to show how vitally important iron is in our lives.

There is no denying—human society would be unable to exist without iron which accounts for about ninety-five percent of all metals produced in the world. Throughout the centuries iron has been playing the role of the chief metal of construction. But what would happen if other metals vanished from use? Although they are made and used on a far more modest scale, the world deprived of aluminium, copper, zinc, lead, titanium, magnesium, nickel, chromium, tungsten, molybdenum, tin, and silver would look not a bit more cheerful than in Fersman's book.

Indeed, aviation and civil engineering today are unthinkable without aluminum. Without copper, electrical engineering would have all but to close down its activities. Devoid of chromium and nickel, stainless steel would fall an easy pray to rust. Without tungsten, there would be no other way to make thousands of millions of electric bulbs. We needn't go on with this sad inventory of changes, though, because every metal performs its 'personal' services for present-day technology.

Curiously enough, there have been many who didn't share this, it would seem, obvious point of view. During the Middle Ages, quite a few of those who claimed to be scholars maintained that metals were of no use to man and one oughtn't therefore to rummage in the Earth's sacred entrails in search of ores. In his retort to the self-styled experts, Georg Agricola, a prominent German thinker who lived in the 16th century, the author of many works on metallurgy, including his fundamental book "On Mining and Metal Making" which saw the light of day in 1556, wrote: 'Man cannot manage without metals... If there were no metals, people would be dragging a most loathsome and miserable life among wild beasts. They would revert to acorns, wild apples and pears, grass and roots; they would have to dig out shelters with their nails for the night, and would be roaming in the woods and fields like beasts in the daytime. Since this way of life would be utterly degrading to man's intellect, the best gift Nature could confer upon him, could anyone be so foolish and stubborn as to deny that metals are indispensable in providing food and clothes and that they generally serve to sustain human life?"

Mihail V. Lomonosov was of an equally high opinion of the part that metals play in man's life. As he wrote in his book, "A Word on the Usability of Chemistry": "Metals give strength and beauty to the things of importance to society. We use them in defence against an enemy, they go to hold together ships so they can stand up to storms and ply the high seas. Metals are used to plough the soil and to make it fertile. Metals are used to trap land and marine animals which go to feed us. In short, there is not a single art or craft which could do without metals." Metallurgy, he adds, "is the source of all internal wealth".

That's true every bit—our life is unthinkable without metals. Since the Stone Age relegated its powers to the Copper Age, metals have faithfully been serving man, helping him to build and create, to tame the elements, to unravel Nature's secrets, and to devise remarkable machines and mechanisms. None the less, the only materials that our prehistoric forebearers knew for about two million years were stone, wood, bone, shells, and clay, and they hadn't the slightest idea about metals. When was it that man made his acquaintance of metals?

As scientists believe today, this happened just a few millenia ago. If we agree to count the time that has passed since the start of the Stone Age to our times as a day, we will find that man has been dealing with copper, gold, iron and other long known metals for only a few past minutes (and just a few instants in the case of many of the metals discovered recently). It is during these 'minutes' that our civilization has been created and has achieved its summits. It is these 'minutes' that encompass all of man's historically observable biography.

It must be admitted, though, that some literary sources mention amazing facts which (if they had been authentic) might confirm that our civilization has forerunners which had reached a high level of development in material culture before they disappeared from the face of the world. It is alledged, among other things, that when, in the 16th century, the Spaniards landed in South America, they found an iron nail about ten centimetres long in a silver mine in Peru. The find would have hardly brought about any interest but for one circumstance: for a great part of its length the nail was firmly cemented in a piece of rock, and this could mean only one thing: it had been lying there for tens of millenia. At one time the mysterious nail was, it is maintained, kept in the office of Fransisco de Toledo, the Peruvian Vice Roy, who made it a habit to show the thing to his visitors.

Other similar finds have also been reported. One is a seemingly worked iron meteorite discovered in Tertiary coal seams in Australia. But how could it be possibly worked in days tens of millions of years remote from our times? For even such a fossil 'oldtimer' as Pithecanthropus lived much later—just five hundred thousand years ago.

Another report about a metal object found in a colliery in Scotland was carried by a special journal, 'Scotish History Society Publications'. There is one more find of what we might say 'mine' origin: it was a golden chain allegedly found in a coal seam in 1891. Only Nature could have been able to encase the chain in a lump of coal, and this could happen only when coal was just being formed.

But where are all of these finds—the nail, the meteorite, and the chain? For present-day techniques of dating and analysis would be able to tell us a good deal about their origin and age, thus unravelling their mystery.

Unfortunately, nobody knows today where they are. But again, did they ever exist?

Since the previous civilizations have not left other, more convincing proofs, let's go back to our time which, too, offers quite a few occasions for meditation and amazement. For isn't it amazing that some tribes are still living in a Stone Age environment at the end of the 20th century when the Copper Age, the Bronze Age and, indeed, the Iron Age seem all to have moved into the past? Man today is well equipped to probe deeper and deeper into the hard-to-reach regions of Africa, South America, and the multitude of islands scattered in the oceans. Quite often the explorers run into archaic communities which seem to have migrated from other, long passed times into our days.

Quite recently, West German ethnographers ran into the Batusuns, a tribe untouched by civilization, in the swampy jungle of eastern New Guinea. The natives didn't seem to know either iron or other metals and used stone axes and other tools and utencils made of stone and wood. When the ethnographers showed the natives several broad, heavy knives, known as machetes in Latin America and the West Indies, the Batusuns touched the sharp blades and, wonder-struck, clicked their tongues in an appreciation of the strange, unknown weapons.

Many famous travellers of the past, too, told of their encounters with 'other-timers'. When he first stepped on the soil of the hitherto unknown America, Christopher Columbus was surprised a good deal when he learned that some inhabitants of the newly discovered continent didn't know iron. "They do not know or wear weapons. When I showed them my sword, they caught at the blade and, through ignorance, cut their fingers. They have got no iron. Their darts and clubs are without iron. For arrowheads, they use either fish teeth or some other materials".

It is interesting, in this respect, to turn to the diaries of James Cook, the distinguished 18th-century English navigator. They carry quite a number of stories about the natives of Polynesia—the islands of the Pacific. They were quick in realizing the value of iron when they first saw it. As Cook recalls in his diaries, nothing lured the visitors so much as iron—it was always the most coveted and the most valuable merchandise. One day, Cook's sailors exchanged a rusty nail for a whole hog. On another occasion, the islanders gave the sailors so much fish for a few old and useless things that the crew ate it for several days. Because of nails and other iron things, the matters on board the ship made a dangerous turn: not only would the sailors pull out nails wherever they could, but they even made an attempt to steal an anchor so as to melt it and to make new nails. Cook was forced to take strict measures: he issued an order threatening with a severe punishment to any one who would try and steal any iron from the ship.

Far more surprising things happened on a distant Pacific island. When Cook and his sailors landed there, they gave a handful of iron nails as a present to the hosts so as to win their favour. The natives, however, must have never seen those metallic things before. Obviously puzzled, they turned the nails round and round in their fingers. Nothing came out of an attempt to explain what the nails were for.

Help came from the supreme priest apparently held in high esteem as an expert on any issues. Taking upon himself an imposing air, he uttered something wise, and his tribesmen buried the nails in the ground. Now it was the guests' turn to show surprise. On seeing their bewilderment, the natives explained with their fingers and other signs that the iron sticks planted in the ground would soon grow into trees hung with bundles of nails like bananas. The islanders intended to reap a bumper crop of metal fruit and to vanquish all enemies with iron's help.

During the many centuries of his history man has learned how to mine, smelt, and work many metals, among them iron, the chief metal of present times, which has given the name of Iron Age to the most significant and productive period in the development of human society.

The Deeds of Bygone Days

The Gifts of the Anatolian Hills

As If From a Horn of Plenty — The Venerable Age of Chatal Hüyük — A Turn of Good Luck — Masterpieces of the Ancient Jeweler — One More Surprise — Five Centuries Older

In 1951-52, the British archaeologist James Mellart was busy with his excavations in the Anatolian Plateau, Turkey. The finds were few and far between, and the scholar felt it was time to stop his search. Indeed, man had settled in the region in a recent past (by historical standard, of course), as students of ancient history maintained, and there was not much sense in going on with the excavation.

When he was leaving Anatolia, Mellart didn't know if he would ever come back there. Sure enough, he hadn't the slightest inkling that he was destined to make, just a few years later, a discovery which would be hailed as a sensation in the world's archaeological community. But time and again he would see in his mind's eye the large twin hills in the valley of the river Konya: he hadn't had time for them. There was something that would drive his thoughts back to the twin hills—that's what Chatal Hüyük stands for in Turkish—towering amidst the salt steppe.

Anyhow, a November morning in 1958 saw Mellart and his colleagues from the British Archaeological Institute's School in Ankara climb to the top of the eastern hill of Chatal Hüyük. They had just got down to work when finds began coming up one after another. It looked as if the hill was in a hurry to part with its secret it had kept for centuries.

First the archaeologists ran into traces of adobe houses, stone artifacts, and animal bones, then they came upon farming implements, grains of wheat and barley, peas, and grape pips. Everything told them there must have been homes of ancient tillers and cattle breeders. But from what time?

As radiocarbon dating showed, the settlement had existed somewhere between 6500 and 5700 B.C., or eight and a half millenia before. So venerable an age couldn't but stimulate immense interest in this remainder of the neolitic times.

In 1961 Mellart began systematic excavations, and a turn of good luck wasn't slow in coming, more than offsetting his fruitless search of ten years before. He found rather well preserved huts, hearths, poles that once supported roofs, and utencils. Chatal Hüyük was no less lavish in pieces of ancient art, such as multicolour wall frescos, bas-reliefs, elegant figurines, and ceramic ware.

But most valuable to any archaeologist were the small copper things found in one of the lowest (and therefore the most ancient) strata of the excavation: copper awls and tiny beads and tubes used to add beauty to women's clothes.

What was so valuable in those uncomely pieces of copper, tarnished and green from time?

The point was that they were made of copper—known (at the time) to be the oldest metal used by man.

At first Mellart thought it was lead, but when the finds were analysed, the verdict was 'copper'. It was quite reasonable to think (as Mellart did), that the copper once used by the ancient inhabitants as a material for their artifacts was native—that is, one occurring as such in nature. But Chatal Hüyük had one more surprise in stock for archaeologists and historians of metallurgy: the workers who did the digging found a lump of copper-smelting slag in the same lowermost strata. Obviously, Chatal Hüyük's artisans had known not only how to work native copper but also how to smelt the metal from ore.

The discovery was of utmost importance to archaeologists and historians.

Although a party of American and Turkish archaeologists working in the upper reaches of the river Tigris not far away from the Konya valley soon after Mellart's discovery found the remains of an ancient settlement with traces of copper and copper ore about five centuries older than the one at Chatal Hüyük, it is these twin hills on the Anatolian Plateau that have rolled back by nearly three millenia the presumed time boundary for the origin of metallurgy on the Earth, and have come down into the history of archaeology as one of its brilliant pages.

Bronze Takes Over From Copper

The Find Near the Great Lakes — Advantages Present Themselves — The Pharaoh's Favorite Kettle — The Sun Has Spots, Too — In Partnership with Tin — 'Copper from Brundizium' — The Picture on the Tomb's Wall — Everything in Its Time

Before they learned how to extract metals from ores, our forebearers in most regions of the ancient world used lumps of native metal picked from the surface of the ground. Nature was not stingy about such 'presents', and they were sometimes quite large in size. We know, for example, of gold nuggets as heavy as a hundred kilograms and of lumps of silver tipping the scales at several tons. Lumps of native copper were especially big in size. In the mid-19th century, for example, a cluster of larger copper nuggets weighing about four hundred tons was found near the Great Lakes in North America. Their faces still bore the traces of stone axes with which man way back in the neolithic time chopped off pieces of copper for his needs.

And the need for copper was great indeed. The advantages that copper had over stone as a material for weapons, tools and utencils were so obvious that the ancient tiller, cattle-breeder or hunter could not but notice this. The metal had many good things about it: it could readily be worked to any shape, flattened, pointed, and holed.

Copper, it seems, was the first metal to begin ousting stone. At first, man made it into small things such as arrowheads, direct from the nuggets he had happened to find. Before long, however, man may have noticed that when hammered cold the copper piece would become harder and stronger, but when held over a fire it would become soft, malleable, and easy to work.

Time passed. Gradually acquiring skills in the working of copper, man reached noticeable proficiency to which the copper things made by ancient artisans are a witness. One of them is the large kettle made of hammered copper sheet and found in the tomb of an Egyptian pharaoh who lived somewhere in the mid-3rd millenium B.C.

Following that, man learned how to melt copper and to cast it into simple shapes. Although the most ancient of the castings known to historians, an axe cast into an open mould, is nearly six millenia old, man must have learned the true art of casting after a 'course of instruction' in the hot working of metal.

The advantages that copper had as a material were undeniable, but even the Sun has spots. One such 'spot' for copper was its relatively low strength: copper knives, axes and other weapons and tools would become blunt before long and had to be reworked. That was the reason why stone remained man's reliable helper and went on competing with copper for a long time.

Before it could oust stone from this segment of material culture, copper had had to enter into alliance with another metal, tin. An alloy of copper with tin, known as bronze, outperformed copper on many counts: it was harder and stronger, less apt to corrode, and a blade made of it was springier and sharper. On top of that, it melted at a lower temperature than copper, it filled a mould better, and gained more strength when hammered cold. Now the days of the relatively short Stone Age were counted, and it gave way to the reign of the Bronze Age on our planet.

Man first made bronze somewhere in the 4th millenium B.C., it seems: that's how archaeologists date the earliest bronze weapons and tools found in Iran, Turkey and Mesopotamia. But the alloy was named 'bronze' much later. That's how it may have happened.

One of the oldest seaports of Italy, Brindisi was in ancient times (when it was called Brundisium) the terminal point of the Appian Way, a magnificent highway extending from Rome, over which the copper produced at various mines throughout the country arrived to go to many other places. However, the copper was pure very seldom; as a rule, it would carry some amount of tin; when smelted, the two metals would produce an alloy in a natural way— 'copper from Brundisium' ('ex Brundisi' in Latin) or, through corruption, '*bronze*'. Or this may have happened in a different way: Brundisium was a port of arrival for the many ships that brought tin from the British Isles. The local metalmakers may have noticed that the union of copper and tin whose roads crossed at Brundisium made a good product and ventured to make it on a 'mass scale'. And again, through corruption, copper from Brundisium turned into *bronze* which spread over the face of the ancient world before long.

It may be added, though, that some metals, other than tin, such as lead, arsenic, antimony, aluminium, beryllium and chromium, when added to copper also improve its properties. But of all the likely copper-base alloys, tin bronze is most widely known.

An interesting picture which shows the way bronze castings were made in ancient times has been found on a wall of an Egyptian tomb dated from the mid-2nd millenium B.C. Three men (apparently, slaves because they are watched by a slave driver with stick in hand) are carrying a charge of metal to a hearth where it is to be melted. We can clearly see crucibles, heaps of charcoal, and the basket in which it is carried to the foundry. Two other men are seen to attend to bellows, and still another is armed with a poker—the three keep the charcoal in the hearth aglow. Using rods, two more men are seen pulling a crucible holding molten bronze from the hearth and carrying it to a mould. The ancient artist added a 'legend' to his picture: the hieroglyphs say that the picture shows the casting of large bronze doors for a temple and that the metal had been brought in from Syria on the Pharaoh's order.

Before long bronze found its way into many regions of the ancient world. For over two millenia (from the late 4th to the early 1st millenium B.C.) it remained the most important material not only made into weapons and tools, but also cast into statues and turned into pieces of art and decorations. The Bronze Age made an extremely valuable contribution to the progress of material culture. However, bronze too was destined to gradually give way to another metal—iron which claimed, and quite justly at that, the role of the chief metal of civilization.

The Metal From the Sky

Why Is It So Scarce? — The Giant from Africa — From Cape York to New York — The Crater in Arizona — Miscalculation of French Academicians — The Pallas Iron — The Necklace from Egypt — Taking the Place of the Bronze Age

Historians class iron among the first metals to have been found by man in native state. However, while copper, gold, and silver are a fairly frequent occurrence in the form of Nature-prepared bullions, it is a truly formidable task to find a nugget of iron on our planet—about as easy as to lead a camel through a needle's eye. Why is it that native iron is so scarce? The point is that when exposed to the terrestrial atmosphere iron quickly reduces to ill-famed rust.* On the other hand, archaeologists have found a multitude of objects made from iron when man still didn't know how to smelt metals from ore. How could he possibly procure it (I hope the reader will forgive me for using this 20th-century word)?

This metal literally fell from the skies. Studies have shown that the iron used by man at the dawn of civilization was of cosmic origin: it was part of the meteorites reaching the Earth's surface from outer space. Quite aptly, iron is called the heavenly metal in some languages.

Many thousand tons of meteorites carrying close on ninety percent iron reach the globe's surface every year. As a rule, the meteorites arriving at the Earth's surface are small in size, usually not more than a few kilograms in weight, although some rare specimens may be several tons heavy. The largest iron meteorite was found in South-Western Africa in 1920. Named 'Goba', this heavenly traveller tips the scales at about sixty tons.

When he was on one of his expeditions to Greenland at the turn of the century, Robert Edwin Peary, an American rear-admiral and explorer, found a huge rock half-buried in the ground near Cape York, the northern tip of the island. The lump was an iron meteorite which had fallen on the Earth nobody knows when. It seemed to have served as a natural source of iron for the local inhabitants for centuries. As a need arose, the Eskimos would chisel off a piece or two and hammer them to whatever shape they might want. That was how they made their knives, tools and other things.

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* Curiously, the samples of lunar soil brought back by *Lunas*, Soviet automatic lunar probes, and *Appolos*, the American manned spacecraft, carry extremely small particles of pure iron without the slightest traces of oxidation. Why is it that terrestrial and lunar iron differ so greatly in behaviour? Why is that iron on the Moon remains untouchable for oxygen? We will go back to these questions a bit later.

It will remain unknown for ever how much the traveller from outer space had lost in weight during its stay in the ice of Greenland, but at the time Peary found it, its weight was about thirty-four tons. It was a tall task, indeed, to move the meteorite to New York where it has since been kept in the Museum of Natural History.

However, history has records of far heavier meteorites which have ended their travel on the Earth's surface. In the late 19th century, a huge crater measuring twelve hundred metres in diameter and one hundred seventy five metres deep was found in the Arizona Desert, USA. It was made by a giant iron meteorite that had fallen in prehistoric times. The Americans took a good deal of interest in the meteorite, the more so that rumours were flying that platinum was found in its fragments. They even set up a company to exploit the meteorite for industrial purposes. It turned out not at all easy to 'cash in' on the present from the skies: a diamond drill broke just as it had reached the meteorite's core at a depth of four hundred twenty metres. Since no platinum was detected in the drilled-out specimens, the meteorite businessmen closed down their venture. As scientists believe, the Arizona meteorite weighs several hundred thousand tons. It is not at all unlikely that this 'iron deposit' will stimulate interest some time in the future again.

In Soviet territory, too, there is a similar 'store' of iron. From a careful study of the Zhemanshin Crater near the Aral Sea, Kazakh explorers believe that a huge iron meteorite measuring nearly four hundred metres across landed there over a million years ago. As seismic sounding has shown, the crater filled with a mixture of minerals produced as the meteorite struck the Earth's surface is more than six kilometres in diameter and seven hundred fifty metres deep. Currently, geologists are busy analysing the minerals filling the crater; it is not at all unlikely that an extremely rich deposit of iron will be found there with time.

Believe it or not, but even in the late-18th century many prominent scientists thought it inconceivable that the Universe could supply the Earth with iron. In 1751, a meteorite fell near the German city of Wagram. Forty years later, one of the professors in Vienna wrote: "Just imagine that in 1751 even the most enlightened persons in Germany believed in the fall of a piece of iron from the skies—this shows how little they knew of the natural sciences... But nowadays it is unforgivable to take such tales at their face value".

A similar view was held by the famous French chemist A.L. Lavoisier who thought, along with some of his colleagues, that "it was physically impossible for stones to fall from the sky". Count Berthollet, another chemist of no less fame, echoed: "These legends cannot be explained by either physics or by anything reasonable". In the wake of these strong opinions, the Royal Academy of Science in Paris even ruled that reports about the falls of stones on Earth should never be discussed again. The academicians were dead sure that all this 'yarn' about visitors from the sky was simply preposterous.

But unaware of the academicians' flat refusal to recognize them, meteorites went on arriving at the Earth's surface quite often, thus leaving the savants amazed and even bewildered. Finally, a shower consisting of thousands of stones fell at L'Agile, France, on April 26, 1803. This event changed the thinking of the Royal Academy, and a commission appointed to look into the matter reported that these stones did come from the sky.

The USSR Academy of Sciences' Mineralogical Museum has a huge collection of meteorites. Exhibit No. 1, which has started the collection and the very science of meteorites, is a mammoth boulder called the Pallas Iron.

It was found on the steep bank of the river Yenisei about two hundred kilometres from the city of Krasnoyarsk in 1749. While hunting in the area, the local smith Yakov Medvedev hit on "a blob of boiled iron quite on the surface at the top of a high mountain". Even before that the local people had heard about an amazing iron boulder lying somewhere on the right-hand bank of the Yenisei. To believe the Tatar elders who lived in the nearby villages, the boulder had come from the sky sent by Allah himself many years before.

The smith must have thought there was some of Nature's secrets linked to the unusual boulder, and decided to move it closer to his homestead. According to a contemporary, "Medvedev moved all of the boulder with great difficulty to his home village Ubeiskaya some thirty kilometres away, now called Little Medvedevka".

Finally, word about the mysterious boulder reached P.S. Pallas, Fellow of the Russian Academy of Sciences. Yakub, a retired Tatar soldier and a friend of Medvedev's showed Pallas when he came to Krasnoyarsk several pieces he had chipped off the boulder. They intrigued the scientist. As he recalled later, "I sent the Tatar without delay to Medvedevka and told him to bring all of the stone which weighed forty-two poods (six hundred seventy-seven kilograms) to Krasnoyarsk".

When he saw it in the city, Pallas was struck by its size and texture. As he wrote, "The stone had a stiff iron crust fitting to it like a coat. Hidden under this thin crust, the core consisted of iron, white at fracture and spongy, with round and oblong balls enclosed in its cells".

In the summer of 1773 what later came to be called the Pallas Iron was moved to St. Petersburg where it was given a pride of place in Peter's Museum of Antiquities.

Pondering over the origin of the Krasnoyarsk find, Pallas justly thought it couldn't have been man's creation. As he reasoned, "If, on the other hand, this could, against all probability, have happened, why is it that the boulder, so heavy, was moved to such a high mountain and why is that it was left on the surface unused?". Finally Pallas concluded: "This iron has been produced by Nature and not by any art. All of its bulk and any tiny part of it unquestionably prove that it is a perfect creation of Nature's". Since Pallas, along with many other scholars of his time, didn't believe that stones could fall from the sky, he left the Iron's mystery unravelled.

It wasn't until 1794 that E.F.F. Chladni, Professor of the Berlin Institute and Corresponding Member of the St. Petersburg Academy of Sciences, advanced in his book, "On the Origin of the Iron Bulk Found by Pallas and On Other Similar Iron Masses and Some Other Related Natural Phenomena" the first correct explanation of the origin of the unusual iron: "This matter existed in interplanetary space and has come to our planet from there".

But to go back to the time when ancient artisans, without a single thought of its origin, eagerly used this strong but readily workable material to make a wide range of things by hammering it cold.

One of the earliest iron articles has been found in Egypt: it is a necklace of hammered strips of meteoric iron, dating back to the 4th millenium B.C. Another object, dating back to the late 4th millenia B.C. is a dagger of meteoric iron, found in southern Mesopotamia, at a site once occupied by the Sumer city-state of Ur (now it is Iraq's territory).

There was only one, but extremely important limitation about meteoric iron: meteorites would not come 'on demand', and the demand for iron was heavy indeed. Rather than to wait for presents to come from the sky, man was learning how to extract iron from ore. Finally the time came when man was able to use his own, terrestrial iron and not only the one from the sky. Having learned how to smelt the metal, ancient metallurgists got to know how to carburize and then to quench it so as to make the relatively soft iron both strong and hard. It was beyond the powers of both copper and its alloys to compete with such a material—that's how the Bronze Age gave way to the Iron Age.

Fires in the Distance

Whom We Owe What? — Once in the Heap of Coals — A Million and a Half Years After — The Miraculous Transformation — The Malachite 'Pie' — Nothing Venture Nothing Have — Through Centuries and Millenia

When was it that man first thought that an ore could be converted to a metal? As Lewis Henry Morgan, a prominent American historian and ethnographer, wrote in the 19th century, it wasn't unlikely that the idea to melt ore occurred at some one place, and it would be a special pleasure to learn to which tribe and to which family we owe this invention and, indeed, our civilization.

Historians concerned with primitive society believe that the decisive role in the origin of metallurgy was played by the camp fire. When making a camp fire, our distant ancestors would fence it off against the rain and the wind with stones, and it could well happen that lumps of ore were among them. As a rule, even the strongest flame of a camp fire cannot produce a temperature high enough for the ore to be reduced to the metal. But, presumably, it so happened once that the camp fire had been made very large and maintained for a long time so that the natural bonds between the metal and the oxygen were broken, and the ore stones were turned into heavy, uneven cakes of metal.

The probability of a metal being smelted from an ore in the flame of a camp fire is very remote, indeed: camp fires had been used for nearly a million and half years* before the ancient fire keeper doubled unexpectedly as a metal-maker. But however remote this probability may be, the camp fire hypothesis has practically no rivals and so it remains the only feasible one to explain the advent of primitive metallurgy.

Now that he had been communicated to the sacrement of ore-to-metal transformation, primitive man no longer wanted to depend on a lucky chance — rather, he was bent on learning how to run the process according to his own will. That's how the idea of metal-making conquered our distant forefathers.

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* The traces of the Earth's earliest camp fires found near Lake Victoria in Africa are 1.4 million years old—that's the geological age of the strata in which the camp fires have been found.

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In their study of ancient metallurgy, historians have more than once tried to re-create the conditions in which primitive man smelted metals from ores.

In 1938, a British scientist made an interesting metallurgical experiment: he tried to smelt copper from the mineral malachite, using an ordinary camp fire instead of a copper smelting furnace. For this purpose he had made a 'pie' in which layers of malachite alternated with layers of charcoal, and then ingnited it.

As the experimentor had hoped, the fire would produce a temperature of 700-800°C which would be enough for copper reduction. But the fire disappointed him: the copper carbonate (making up the mineral malachite) was merely turned to copper oxide—the reaction didn't go any further and no pure copper was made. But as the saying goes, you must spoil before you spin, so the scholar wasn't put out of confidence. After a 'post-mortem' of what he had done, he pin-pointed the culprit: it was atmospheric oxygen which prevented the copper from getting rid of its own oxygen.

In a repeat experiment, the experimenter put his flaky 'pie' in a pot, closed it with a lid, covered with a blanket of coal to make sure, and finally put a fire to it. Now, no atmospheric oxygen could find its way to the reaction zone, and the copper carbonate reacted with the carbon monoxide produced by the burning coal to leave pure copper.

A similar experiment, but with iron ore, was made by the Soviet archaeologist B.A. Kolchin and his co-workers in the early 1960s. Drawing upon what was known about primitive metallurgy, they built a small charcoal hearth. The charge was made up of rich bog iron ore and high-quality charcoal. A steady blast was maintained throughout the operation and the temperature was measured at several levels of the burden (of course, ancient artisans had to do without all of these niceties for 'technical reasons'). For all the precautions taken, the experimentors failed to produce a good iron bloom. Their product was highly slag-laden, spongy iron which refused to be hammered dense, no matter how the experimentors tried.

However, even this, seemingly unsuccessful experiment was beneficial to historical science: it came as another proof that iron making in ancient times demanded high skills from the primitive metallurgist. It is no mere chance that among all nations metal-makers have since old times been held in high esteem and respect which man has preserved through centuries and millenia.

The Hearth Turns Into the Blast Furnace

The Iron Age Takes Over

Did As They Once Used To — On the Slope of a Mountain — The Race Against the Wind — The Mystery of the Hittite Kingdom — The Pharaoh's Request — The Miraculous Column in Delhi — For a Rainy Day?

There is, on the western shore of Lake Victoria in Africa, a village where the ancient tribe of Hayas lives. Now they grow cattle, bananas, coffee and tea. They have to 'import' metal tools and other articles because they have no iron of their own. It had been held for a long time that the natives didn't know how to smelt iron. When, however, the explorers studying the tribe asked the chiefs, the old men convincingly refuted the false idea.

Working deftly, a group of eighty-year-old men built a cone furnace a metre and a half tall, using the earth from a termite castle. They dug out a pit about forty centimetres deep under the furnace and tamped it full with charcoal they had made by burning cane. After they had blown in the furnace, they went to charge coal and ore through its top while feeding air through cane tubes from a goat-hide bag. Eight hours later, when the temperature had been brought up to the required level, the ore turned into molten iron-silicate slag where crystals of iron then formed.

It turned out that the old men had been smiths more than a half-century before, but the tribe had decided that they would gain more by buying 'foreign' metal products than by making them on their own. The former smiths had learned other crafts, but when, an occasion had presented itself, they were pleased to do as they used to when they were young men, and demonstrated their skills to the explorers.

The excavations made on the shores of Lake Victoria discovered thirteen smelting furnaces in which iron was made some fifteen to twenty centuries before. Now we know that the ancient African civilization of nearly two millenia ago was advanced in the art of metal-making far enough for an ore to be turned into carburized iron with the aid of an air blast.

The use of an air blast was an important step forward in the progress of metallurgy. Already in the early days of smelting, man noticed that the wind would foster the burning of the charcoal in the hearth and speed up the conversion of the ore to the metal. This observation prompted ancient metal-makers to dig smelting pits or to build small furnaces from stones given a coat of clay on the windward slopes of high hills or mountains.

Unfortunately, it wasn't always that the wind would blow in the right direction. As often as not, it wouldn't 'report for duty' at the furnace at all, sending instead a light breeze failing short of what smelting technology called for. Or a dead calm would set in. In short, one might as well stand at the hearth and blow into it at the top of one's lungs.

Indeed, that was what the early metal-makers must have done at first, but sooner or later it should occur to an ancient inventor that they could use some sort of mechanized blast: so air came to be fed into the hearth through special pipes and the human lungs were replaced with bellows sewn from animal hides.

What a difference the air blast made! As one would say today, the process showed a far better performance: a good deal more of pasty or semiliquid iron would now be found at the bottom of the hearth than before. This technique has come down into the history of metallurgy as the cold-blast process because the air blown into the hearth was cold (the hot blast didn't appear until the 19th century).

The iron sponge (bloom or ball) produced in a cold-blast hearth carried a good deal of slag—the molten barren rock. In order to remove it, the bloom or ball was hammered: this squeezed the slag from the iron, the metal became dense and turned, or was wrought, into a solid piece, known as wrought iron, to be used in further forms of working.

Where was it then that the metallurgy of iron was first devised? What region of the world was the first to use this metal? When did it spread over the face of our planet?

No single answer can be given to these questions. Until quite recently historians believed, on the basis of archaeological data, that the metallurgy of iron was born in the Hittite Kingdom, a state which existed in Eastern Anatolia (Asia Minor) in the 2nd millenium B.C. Many scholars shared a hypothesis by which the Hittites had invented the iron-making process and held it under a veil of utmost secrecy. It was largely due to iron, of which they had large quantities, that the Hittites flourished so high in the 16th to the 13th century B.C.

Since other peoples didn't possess the secret of iron-making, they valued the metal more than gold. In ancient Rome, for example, they used to make wedding rings from iron. Only noblemen were able to wear iron 'jewelry' often set in gold. As Homer tells us in his *Iliad*, Achilles, the hero of the Trojan War, presented a discus made of an iron bloom to the winner of a discus-throwing contest. During the excavation of an Egyptian tomb the archaeologists found, among other valuables, a necklace in which iron beads alternated with those made of gold.

From the documents that have reached us, we know that an Egyptian pharaoh asked the King of Hittites to send him some iron in exchange for any amount of gold. In the Pharaoh's words, he had got as much gold as there was sand in the desert. But, apparently, he was hard pressed with iron.

In the early 12th century B.C. the Hittite Kingdom fell to pieces and ceased to exist, and other peoples learned the secret of iron making from ore. As it ousted bronze, iron was finding its way into many corners of the world. At least, that's how it was believed to be until recently. The archaeological finds made in the few past years, however, have shown that the people of ancient Thailand knew how to make iron somewhere in the 16th century B.C., that is, well before the Hittites. Traces of iron smelting and working from ores dating back to the mid-2nd millenium B.C. have been found in Central Asia, Africa, India, and in the Mediterranean region.

Although the natural stores in ancient Egypt were not rich in iron ores, the Egyptians were good at working the metal. It is in Egypt that archaeologists have found the world's most ancient objects made of cold-blast iron. The finds made in an Egyptian pyramid include, among other things, a blade several millenia old. The foundation of a sphynx in Karnak, the famous group of temples near Luxor, Upper Egypt, built between about 2100 and 1250 B.C., has preserved for historians a sickle made of iron several centuries before Christ.

Artisans in ancient India, too, were great masters of making and working iron. This is convincingly proved by the famous Iron Pillar, one of Delhi's many historical attractions.

The Iron Pillar was set up in A.D. 415 in memory of King Chandrahupta II who had died shortly before. At first, it was installed in front of a temple in eastern India, but it was then moved to Delhi in 1050. The Pillar weighs about six and a half tons, stands seven metres and twenty centimetres tall, and has a diameter of forty-two centimetres at the base and thirty centimetres at the top. It is made of nearly pure iron and shows no traces of rust.

How could the ancient masters make this miraculous pillar before which time itself is impotent? Some science-fiction writers tend to believe it was made on some other planet and was then carried to Earth by the crew of a space ship as a message or a gift to Earthlings. There is another body of opinion which holds that the Pillar was wrought from an iron meteorite.

It is more likely, however, that the truth lies in the words of those who believe that the Pillar owes its existence to the extremely high skills of ancient Indian metal-makers. India has always been famous for its iron and steel products, and it is no mere chance that the Persians had a proverb saying something about carrying steel to India—not unlike the English proverb about carrying coal to Newcastle. Apparently, the Pillar was fabricated from large individual iron balls welded together in a smith's forge—a feat extremely difficult to emulate even today.

By the 1st millenium B.C. iron had spread to many developed regions, but it remained to be valued high and the demand for it was growing all the time. The following fact bears out the point. As part of their excavations in Nineveh, the capital of ancient Assyria, archaeologists dug out the palace of powerful King Saragon II who reigned from 722 to 705 B.C. and found in it a veritable warehouse of iron objects: helmets, saws, smith's tools, and also unworked iron blooms which, it seems, the thrifty king had put aside for a rainy day.

Masters of the Smelting Art

Chosen by Spirits — One Spring Many Thousand Years Ago — The Proprietary Secret — In Tales and Myths — The Dance Around the Sieve — The Energy Crisis in Ancient Egypt — From Dawn to Sunset — Learning from Mistakes

The art of metal-making has been wrapped in a veil of mystery since ancient times. Perhaps all ancient tribes and peoples held those who knew how to win ores and to extract metals from them in high esteem and respect and gave them rights and priviliges sometimes denied to chieftains and priests. This was to underscore the social value of metal-winners.

As a rule, the secrets of metallurgy were known to just a few members of a tribe. They were looked upon as the ones chosen by the Spirits of Fire who had conferred upon them the power of converting stones to metal. Of course, the important know-how wasn't to be passed on just to any one and just at any time; it was only during an initiation ceremony when youth were proving they were worth to be called men that the masters of the smelting art would in a special way (known only to them) transfer to the best of the younger generation their mysterious power over fire; it was only after such a ceremony that the youth would be eligible to mine, smelt and work iron, copper, and bronze. Since, however, the best among the youth were chosen not by spirits but their spokesmen on the Earth, that is, by the masters, it was usual for the sacred rights and trade know-how to be passed down by right of succession, and so the art of metal-making would ordinarily become a family business.

Metal smelting was equated with a religious rite, and it was always accompanied by suitable rituals, and their observance was essential so as to make the whole undertaking a success. A veritable code of unwritten rules prescribed all the operations involved in the making of a metal: the construction of a smelting furnace, the search for and winning of the ore, its preparation for smelting, the choice of suitable wood to be used as fuel, smelting proper and, finally, hammering. Many of these rules and rituals related to metallurgy have lived through millenia to reach our times, as witness the ethnographers who have studied African tribes.

In one tribe, for example, the masters would begin their metal-making campaign only in spring. With the opening of the smelting season they would leave their huts and move to pre-selected nooks, usually away from their village. There, hidden from a foreign eye, they would build their furnaces. In doing so, they were not to use water because it might prevent fire from 'pulling' the metal out of the stone. Nor could they come near their permanent residences or mingle with their tribesmen for fear of loosing even a tiny bit of their power over fire. It was usual for them to bury miraculous drugs and roots which, they hoped, could play an important role in smelting.

At last the furnaces would be complete—now they were to be dedicated. For this occasion the tribes had 'proprietary' rituals, each of its own. In one, a baby placed in the still unfired furnace would be shaking dry beam pods in its hands to imitate the crackling sound of a fire, thus getting the furnace ready for the hot embrace of the flame which would soon make an uproar.

The laws of many tribes required that the smelters should work naked. Although their usual attire would consist of nothing more than a loincloth, they were to part even with it during the smelting operation. Lest the masters of the smelting art should be distracted by worldly affairs, women were banned from the premises of the 'iron works'. It was usual, too, for the smelting operation to be accompanied by music and ritual songs performed by the iron-makers themselves.

Not all of the smelting rituals were so harmless: as often as not a human life would be sacrificed to placate the spirits. This is what A. Bryant, an English ethnographer, writes about the unpleasant traits (to say the least) of Zulu metal-makers: "Their know-how might inadvertently be disclosed during a smelting operation. Lest this should happen, the smiths* always made it a point to work in a remote corner, in solitude; nobody must be able to see what they are doing. It was believed that the ore would give off its contents in plenty only if it had been sprinkled with human fat. But, as everyone knew, human fat could only be obtained by killing a human being. And, of course, everyone knew that each smith must be in concord with what were called 'secret killers'... Naturally, the smiths themselves were suspected; other people would take care not to approach the smiths' secluded kraals usually located in the thickets".

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* The ancient metal-maker usually doubled as a smith, so both names can be encountered in the literature.

This 'smelting technology' could not but tell to some degree on the reputation of ancient metal-makers: in the tales and myths of some peoples they appear ugly and repulsive, with some physical flaws, a bad and vile temper. But, as the saying goes, it is a small flock that has not a black sheep. More often, folk-tales pass down to us the image of a good-willed and wise master of the smelting and forging art, working for the benefit of people and society.

However important the construction of a smelting furnace might be, it was perhaps far more important to assemble the charge or burden—a mixture of ore and fuel.

How could one find the right stone among the multitude of others? One Mosambic tribe, for example, had a century-tested procedure: every search for ore would be preceded by a sacred ceremony. A large sieve used to screen the ore would be placed on the ground, and a ritual dance would be performed around it. Going through the dance, the people would raise their arms towards the sky, deploring the spirits to deign to the tribe's needs and to grant them the ore stone. It would be naive, as the natives thought, to hope for a successful ore search without such a ceremony.

If the spirits were satisfied with the dance, they would grant the tribe's request, and the 'prospectors' were sure to find suitable stones. The stones would then be carefully placed on soft stretchers made of wood bark, and as carefully be carried to the furnace.

Now a good fuel was to be found. Not just any wood could be used, for the stone and the wood ought to like each other—only then could a good metal be obtained. Of course, the best wood species were those which were able to produce a high heat in the furnace. Excellent charcoal could, for example, be produced from agate and date palms and white acacia. Incidentally, these trees are involved in an interesting hypothesis advanced by archaeologists and historians quite recently.

As Egyptologists have counted, ancient Egypt under Pharaoh Ramses II who reigned from the late 14th till the early 13th century B.C., that is, when metal smelting (mostly copper and bronze) was widely spread in the country, had at least a thousand copper smelting furnaces. They used charcoal burned from palms and acacias which grew on the banks of the Nile delta. Later, as the historians report, the production of copper declined drastically. But it is hardly likely that the Egyptians no longer needed this metal. Why is it then that metallurgy in ancient Egypt suffered a severe setback?

This fact had remained a mystery until it was resolved several years ago with assistance from archaeologists. As the excavations show, the copper industry in ancient Egypt took a steep plunge because of the "energy crisis" that had swept the region in those distant times: a good proportion of the country's meager tree stand had been cut and burned to coal during a relatively short span of time. Charcoal had become hard to be had, and copper output declined.

But let's leave ancient Egypt and go back the Mosambic village which, even in the 20th century, used the practices of metal-making from many centuries ago.

So, the smelting furnace had been built and dedicated, the ore—thanks to the spirits!—had been found, and the charcoal prepared. Now a white powder would be extracted from a termite castle—it would help the flame to pull metal from the stone. Finally, bamboo pipes and a large bag sewn from an antelope's hide would be fitted to the furnace in order to drive in the wind (that is, the blast) without which the ore wouldn't give its metal to the flame.

The smelting operation or heat, as it is technically known, would usually last from dawn to sunset. By the time the Sun was sending its last rays to the Earth, a white-hot bloom of metal would have formed in the furnace. Of course, the heat could sometimes end less successfully: instead of a whole bloom, the metal-makers would only find small pieces. As the tribe's smiths believed, there could be only one cause of the failure: they hadn't been zealous enough in begging the spirits to grant assistance, and they would swear not to repeat the same mistake in future. The bloom of metal would then go under a smith's hammer to be forged to the desired shape.

The Iron Triad

What's New over Three Millenia? — Aristotle Witnesses — Saladin Wins the
Bet — Misfortune Brings Luck — The Unbidden Guest — Division of 'Labour'—
The King Lion of China — The Bishop and the Sow

As to quality, the iron balls produced by the cold-blast process often failed short of their makers' wishes. The ball iron was sometimes not strong and hard enough, and the tools and weapons made of it would become blunt or break very soon. On the other hand, the makers would often find, among the relatively soft balls of iron collecting at the bottom of the hearth, also harder pieces—those which had been in contact with the charcoal. Linking the two facts together, the iron-makers would deliberately enlarge the zone of contact between the iron and the charcoal—as a result, the metal would pick up more carbon. This is known as carburizing nowadays. The carburized metal could satisfy the most exacting user. That was steel which is the backbone of the entire material world even today.

The demand for steel was in excess of its supply almost everywhere, but the primitive steel industry was lagging behind. Strange as it may seem, but the metallurgy of iron had, in the past three millenia or so, remained basically the same: the manufacture of both iron and steel was based on the slow cold-blast process.

It must be admitted, though, that ancient metal-makers used what is known as the crucible process to smelt copper, bronze and iron of high quality. Even Aristotle who lived in the 4th century B.C., mentions the famous Damascus steel, or damascene, made in the crucible. The crucible process was mainly practised in India, Persia and Syria, and Damascus steel was hammered into swords, sabres, daggers and other side-arms remarkably sharp and springy, and was also used to make tools of high strength and durability.

However, the crucible process was practically no good as a way of making steel from ores on a large scale. In fact, it was a refining process by which the previously made raw iron was remelted in small vessels known as crucibles, in order to remove undesirable impurities and to equalize its composition. This improved the structure of the metal, and the better structure served in turn to impart excellent properties to crucible steel.

The steel blades made by the masters of Damascus enjoyed, and quite justly, an especially great fame. As the legend goes, it was with a damascene sword that Alexander the Great cut the Gordian knot which everybody else had failed to undo. According to an Oriental legend, Saladin (Salah-ad-Din), the 12th-century Sultan of Egypt and Syria and general, once challenged Richard Coeur de Lion, the English king, to demonstrate his agility and warrior's skills. King Richard cut in halves the lance of one of his knights with a powerful stroke of his sword, thus demonstrating the strength of his blade and his own might. In a reply, Saladin threw a fine silken kerchief up in the air and cut it while it was falling, which was a proof not only of the Sultan's agility, but also showed the unusual sharpness of his sword hammered from crucible steel.

Since very few masters knew the secret of crucible steel, it was made on a relatively small scale. Finally, its secret was lost to civilization somewhere in the Middle Ages (to be revived in Europe in the 18th century).

The demand for steel was growing all the time, and so was the size of the cold-blast hearth, accompanied by improvements in its design and an increase in the strength of the air blast. Still, the process remained a slow one. But, as the Russian saying goes, there is no misfortune without a piece of luck.

By the Middle Ages, the hearth had turned into a shaft furnace which looked like a column several metres tall. The shaft furnace could take in a fairly large charge made up of iron ore and charcoal and needed a lot of air for its blast—many times more than did the ancient cold-blast hearth. Now the furnace "breathed" with the power of water: its lungs, or air bellows, were actuated first by special water pipes, then by large water wheels.

The process in a shaft furnace went on hotter than in a cold-blast hearth: more carbon was burned every unit of time, and so more heat was liberated. It is the high temperature in the shaft furnace that caused some of the iron very high in carbon (and therefore capable of melting with greater ease) to melt and flow out of the furnace along with the slag formed in the course of the heat. (The furnace or, more exactly, its bottom part called, by force of habit, the hearth had a hole to let out any slag.)

On cooling, this iron-carbon alloy carrying many times more carbon than did steel would become very hard but extremely brittle and unmalleable. That was pig iron, so important today, but viewed quite differently by iron-makers several centuries ago. For, when hammered, it would break into pieces, and no weapon or tool could be made of it. On the other hand, this seemingly useless metal did a deep cut in the output of the desirable bloom iron. There was enough reason for medieval metallurgist to be upset.

Quite a number of unflattering names were coined to call this unbidden guest: it was called 'wild stone' or 'goose' in Central Europe, and its name in Russian also refers to swines.

Since no conceivable use could be found for pig iron, it would usually go to a rubbish-heap. This went on until a happy idea occurred to someone to charge pig iron into a furnace again, along with some ore. That's how a veritable breakthrough took place in the metallurgy of iron. As was learned, when re-charged into a furnace, pig iron would yield—with relative ease—the desired steel, and in large quantities at that.

If something of the kind, equal in significance, happened in our days, it would be patented in tens of countries, and the inventor would win world-wide renown. Alas, history has not preserved the name of the medieval inventor, but we know that this happened in the 14th century.

The innovation led to a clear division of 'labour': the shaft furnace, which had now become not unlike a blast furnace, would produce pig iron from ore, and the pig iron would then be re-melted to remove excess carbon in what was known as the bloomery hearth. That was the bloomery process of steel making, carried out in two stages, in which iron ore was first converted to pig iron, and the pig iron was worked into steel. This 'Iron Triad' has retained its significance even now. Although today's mammoth blast furnaces bear only a remote resemblance to the medieval shaft furnace, and the steel-making plant of the latter half of the 20th century doesn't look a bit like the refinery hearth, its ancient predecessor, the two-stage process remains the basis of steelmaking. (The only exception seems to be what we call 'nonblast-furnace metallurgy', to be discussed later.)

One more factor served to promote the use of blast furnaces: metallurgists noted that, when properly treated, pig iron could be turned into what later came to be known as cast iron: an alloy of exceptionally high casting qualities. It came to be widely used to cast cannon, cannon balls, columns for buildings, statues, and many other objects. Historians note that cast iron seems to have been known to ancient masters. Later, the process gained some popularity in other countries. A Chinese foundryman who lived in the 10th century but whose name we will never know made a huge casting of a lion weighing about a hundred tons. Not a single trace now exists of the monastery where the King Lion was made, but the casting is still there to see.

However, the use of iron for casting purposes widely spread at a much later time when the blast-furnace process had been developed to a high degree and was gaining ever more ground. The early books on blast furnaces, too, date back to those times. As tradition had it, books on metallurgy were mainly written by clergymen because the art of writing was more accessible to them than to people from other walks of life. Quite logically, their clerical mentality would often leave a strong impression on their technical writings. A 15th-century manuscript describing some troubles in the operation of a blast furnace says that the fault was cleared through the high metallurgical 'qualifications' of Bishop Antonio of Florence. By his timely prayer, he let the furnace get rid of a 'sow', a large block of solidified iron, the 'sow' melted, and the metal was safely tapped from the furnace.

The Milestones of the Long Road

Czar Peter the Great's Command — Decisive Action by the English Queen — The Tempting Idea — Between Prayers — The Kaleidoscope of Events — At the Close of the Sixth Day — 'The Fire-Driven Machine for Factory Needs'— Ice or Flame? — The Guard of Honour — 'It Has Its Mouth at the Top'

The high demand for pig iron as the primary product of iron-making to be later converted to steel prompted the construction of blast furnaces in many countries. In Russia, the first blast furnace was built in the 1630s. It stood on the river Tulitsa, not far from the city of Tula, with its air-blast bellows driven by water wheels. The furnace was able to turn out as much as about two hundred kilograms of pig iron a day. That was a modest figure, indeed—a good deal less than the huge country needed.

Attempts to find new iron ore deposits were made as early as during the reign of Alexei Mihailovich, Peter the Great's father. One expedition after another was sent to look for iron ores on the banks of rivers and rivulets in many parts of the country. The prospectors were told to locate ore deposits, evaluate their size, manner of occurrence, and how strong a metal it could yield. But they came back empty-handed.

Soon after his succession to the throne, Peter the Great issued a Decree which was to play an important role in the growth of metallurgy in Russia: "Every effort shall be made to multiply the production of every kind of cast and wrought iron... and everything shall be done for Russians to learn the art of iron-making so that this trade could stand firm in the Muscovite State". For those who might conceal the found orebodies, the Decree envisaged "a cruel wrath, an immediate corporal punishment, or death penalty", depending on the gravity of the crime.

Soon a report came from the Urals that rich deposits of lodestone (magnetized iron ore) had been found at Mount Vysokaya: "There is a navel of pure magnet in the middle of the mountain, and around it stand dark forests and stone ridges". The prospectors sent samples of the ore to the capital. The iron that Moscow's masters smelted from it passed the most severe tests. In fact, it was as good as Swedish iron and could well be used to make 'all kinds of gun barrels and locks'. To make assurance doubly sure, specimens of the Ural ore were sent to Holland and to the Tula smith Nikita Antufyev well known to the Czar for his skills. The Dutch experts ranked the ore very high. As they wrote, the iron smelted from it was 'so good in service that nothing could be more durable and softer'. Their view was shared by Nikita Antufyev who made two muskets and two lances from the Ural metal:

"That's a very good iron, not a bit poorer than one from Sweden, and indeed, even better than that for firearms".

It was obvious that the metal industry ought to be developed in the Urals, and Peter the Great issued a Decree on the construction of the first iron works there. In the winter of 1700, the construction of two iron works began, one on the river Kamenka and the other on the river Nevya. Late in 1701, the two works tapped their first pig iron. The Czar gave the Nevya Works to Nikita Antufyev (who later assumed the name of Demidov) and told him to do everything in order that Russia could cease buying iron from abroad. The Works was to manufacture "cannon, mortars, muskets, rapiers, sabres, cutlasses, broadswords, lances, cuirasses, and wire".

Nikita Demidov and, later, his son Akinfy did much to advance metallurgy in Russia. Ural iron was highly valued on the world market. As the English 'Morning Post' wrote in the mid-19th century, the Demidov iron, called 'Old Russian Sable', played an important role in the British industry; for the first time it was brought to Britain to be made into steel in the early 18th century when steel-making in the country was still in its infancy. Demidov iron contributed very much to the fame of Sheffield products.

Among the factors that were favourable to the growth of the iron-and-steel industry in the Urals were not only the riches of the Stone Belt, as the Ural Mountains were known in old Russia, but also the abundance of forests which supplied excellent charcoal for the blast furnaces. Quite logically, Russia was among the world's leading producers of iron and steel at the end of the first quarter of the 18th century. In contrast, the manufacture of iron and steel in other countries where wood was scarce took a plunge for lack of charcoal. That was how matters stood in England which had been the world's leader as an iron and steel producer for a long time.

So much wood was cut and burned to make charcoal in England in the 15th and 16th centuries that the forests were on the brink of complete extermination. A good deal of timber was also needed to build houses, ships, and bridges. There was more than sufficient ground for alarm, and Queen Elizabeth the First issued in 1558 a decree forbidding the use of wood to make charcoal over the greater part of English territory. It appears, however, that iron makers contrived one way or another to circumvent the Royal Decree, so a quarter of a century later a new decree was made public, forbidding some counties to make iron and steel altogether. Later this decree was extended to cover all of Britain. The blast furnaces stood cold without their life-giving fuel, and iron output in the country made a steep dive. Iron had to be brought in from Russia, Sweden and other countries.

The dire straits in which the British iron and steel industry found itself forced the metallurgists to look for a fuel that could replace charcoal. Obviously, they turned above all to fossil coal so abundant in the British Isles. By that time, coal which liberates more heat on burning than charcoal had built the reputation of an excellent fuel, but not for blast furnaces. All attempts to smelt pig iron with coal would inevitably end in a failure: the metal would carry the objectionable impurities sulphur and phosphorus and was practically no good for steel-making.

Still, the idea of replacing charcoal with coal for blast furnaces was too tempting to be given up completely: there was so much coal in deposits all over the country that they could support the iron and steel industry for many years to come. No wonder that many Englishmen, and not only they, tried to solve the problem.

History has preserved for us the name of the Reverend Simon Sturtevant, a German by birth, who was deeply engrossed in worldly 'metallurgical' issues between his prayers. In 1611, he was granted the privilege of using 'sea or mountain coal' for iron-making purposes. But either he soon grew sick of the enterprise or thoughts of saving his soul had filled his perishable existence, Sturtevant gave up his privilege a year later.

Perhaps the first who was able to score a definite success was Dud Dudley, a very young English metallurgist, a natural son of a lord who owned several iron works. In 1619, Dudley was granted a Royal patent saying that its holder had discovered, after a good deal of toil and many expensive experiments, the secret, a method and means of smelting iron ore and making therefrom iron castings or bars through the use of coal in furnaces equipped with blast bellows, the results thus obtained being as good in quality as those obtained before with the aid of charcoal—an invention not yet performed by anyone in the British Kingdom.

Dudley lived a long life full of dramatic events. He had seen many things: his competitors destroyed his works, he was once a prisoner in a London jail for debts, took part in the Civil War, was a prisoner of war and sentenced to death before a firing squad twice, but escaped both times, was heavily wounded, was perfidiously swindled by his partners... Unfortunately, Dudley didn't live in this kaleidoscope of events to see his invention put to practical use. He refused to open his secret to anyone, and when he died, metallurgy was left without knowledge how to use fossil fuel.

It wasn't until 1735, or one hundred and sixteen years after Dudley had been granted his patent, that the blast-furnace process was first carried out, using only coke—a fuel obtained from coal, without which it would be impossible to smelt iron in the blast furnace or to carry out some other metallurgical processes today. The invention of coking has been an important event in the history of industry. It is closely related to the name of the British ironmaster Abraham Darby, Jr.

The Darbys owned an iron works at Coalbrookdale, Shropshire. It was Abraham Darby, Sr., who was the first to experiment with the conversion of coal to coke and with its use in the smelting of pig iron, but he failed to solve the problem fully. The father's work was carried on by his son who was well aware of how important it was to switch the blast furnace to a fossil fuel. It proved a formidable task, however, to obtain coke that would suit their purpose. The experiments that followed one after another took up many years. When the desired coke had been obtained, it was charged into the blast furnace at once. As the family's legend has it, Darby stayed at his blast furnace round the clock without so much as a wink of sleep. Several days passed, filled with agitation and anxiety, hopes and disappointments. It was towards the close of the sixth day that excellent pig iron was tapped from the blast furnace. The happy Darby fell dead asleep right at the furnace, and was carried home, still asleep.

By the end of the 18th century practically all blast furnaces in England had come to use coke. But the change to a fuel of a higher calorific value required that more air be blown into the furnace. The water wheel was no longer able to cope with the task and gave way to the steam engine. As early as 1711, the Englishman Thomas Newcomen, also an ironmonger, invented a steam engine in which the piston was raised by steam and driven down by the atmosphere after the injection into the cylinder of a squirt of cold water which cooled it so that the steam when injected didn't rise up the piston at once. His invention was used to lift water from mines. Four decades later Abraham Darby, Jr. adapted the steam engine to drive the air blower of his blast furnace. But the engine was anything but good and would develop trouble time and again. At the time, two men, James Watt in England and Ivan Polzunov in Russia, were working on Newcomen's engine in an attempt to improve it.

In 1763, while working at a copper smeltery in Barnaul, Siberia, Polzunov devised "a fire-driven machine for factory needs". He planned to build an engine that would replace the water wheel as the prime mover for the iron works, capable of maintaining the blast at the operator's will. Polzunov didn't live to see his brainchild at work: he died in 1763, just a week before his engine was to be tested. For some time, it ran without a hitch, supplying the air blast to three smelting furnaces. However, the Works had no skilled machinists that could attend to the engine. Troubles began to develop, the boiler sprang a leak, and the engine was first brought to a stop and then dismantled.

Fate was more favourable to Watt's invention: in 1784 he was granted a patent for a universal, double-action steam engine. At about the same time, the first steam-driven air blower came to be used by the blast furnaces at English iron works.

The next important step in the development of the blast-furnace process was made about a half-century later when the Scottish inventor James Bomon Nilson proposed to heat air before it was to be blown into the furnace. However strange it may sound, many metallurgists gave a hostile reception to Nilson's idea because the prevalent opinion at the time was that the colder the blast the better it was for the smelting operation. Indeed, air at some works would even be cooled before it was blown in, by placing blocks of ice in the blast pipes. Nilson wasn't a metallurgist but he realized that by preheating the blast it was possible to save fuel and to raise the throughput of the furnace. But how could he prove that he was right? No one among the iron-makers wished to permit the inventor to put his idea to the proof on their blast furnaces.

Finally, the owners of an iron works at Clyde thought they were bold enough to take chances—and they proved right: the test bore out Nilson's idea. In 1828, he was granted a patent on his invention, and the year 1829 saw his remarkable idea realized in practice. Even with a slightly preheated blast, the consumption of coke was cut down by about a third, and half as much again of pig iron was tapped. Before long the hot blast spread widely not only in England but also in other countries, including Russia.

Nilson's air preheater was far from perfection: on passing in cast-iron pipes embedded in the fire-box, air could only be raised to 300-400°C. At a higher temperature the pipes would be overheated and fail very soon. In 1857, the English engineer Edward Alfred Cowper proposed an unusual air preheater for the blast furnace, now known as the hot-blast stove. The early stove was a tall, cylindrical shell rivetted from steel plate. The shell was packed with a checkerwork of firebrick. The checkerwork would be raised to a red heat by hot gases, then the stream of hot gases would be shut off and air would be passed instead. Since the checkerwork had a large surface area, the air could now be raised to 600 or even 700°C. Several years later, Cowper improved his idea by proposing to use the waste gases of the blast furnace in order to preheat the blast.

Before long hot-blast, or Cowper, stoves became a regular feature of all iron works: each blast furnace was fitted with two, three or even four stoves. Even today, many years after, they remain an attribute of any blast-furnace plant. A panoramic view of a large iron works will inevitably show, standing next to any blast furnace, like a guard of honour—huge, blunt-nosed cigars tens of metres tall: they are hot-blast stoves preheating air to as high as 1200°C before it enters the blast furnace.

The smelting of iron in blast furnaces has always emanated a magnetic force. It is no mere chance that many prominent authors who happened to visit an iron works have left picturesque descriptions of how ore is turned to pig iron. For example, the blast furnace greatly impressed Vassily I. Nemirovich-Danchenko, a prominent Russian writer, who described his experience in a featury-story, "At the Ural Works" published in 1890:

"Those uninitiated in the mystery of the mining and foundry art might probably imagine that the blast furnace looks like a healthy-looking and stout village beauty.* Huge and bulky it is, and also beautiful in its own way, but impossibly dirty. It has a huge mouth that swallows tons of ore and firewood, and a stomach that digests the ore to pig iron. That's what the blast furnace is.

"The blast furnace is usually built as tall as a good three-storeyed house. It has its mouth at the top. When the workmen carrying the charge for smelting come up to it, the mouth disgorges a greedy fire which illuminates the dark shed built over the furnace. This produces a very strong impression on a chance visitor like me. There is something infernal in the blaze of the red flame, in the gurgling sound produced by the ore in the bowels of the giant furnace, in the huge and round throat avidly opened in the anticipation of the usual pray.

"Step aside, step aside!" I heard and was pushed out of the way.

"I had hardly had time to come to senses when I saw the place I had occupied just a minute before crowded with charging boxes full of ore and coke. Some twenty-five to thirty-five boxfuls of materials are charged into the furnace every day. The half-naked workmen picked up two more boxes and emptied them into the flame and heat breathing mouth of the furnace. A high shaft of dust, smoke and sparks rose towards the black roof girders. For a moment we, too, were wrapped in the cloud, unable to breathe or to see. The gurgle of the monster rose in strength still more; a far more stronger flame escaped and streamed in all directions, as if wishing to reach us with its fiery stinges. We stepped back against our will, looking at this sacrament from a distance.

"When the furnace had calmed down, its flame turned pure pink and, in a way, beautiful. I was now admiring it, but from a distance, of course. The scene in the shed had become quieter.

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* The point is that the Russian for 'blast furnace' is 'domna' which is spoken and written the same way as the favourite village female name of Domna.—*Translator's note*

"As the smelting operation went on, the ore descended ever more towards the bottom, and the lighter materials, such as coals and fluxes, remained at the top. Pig iron was now boiling at the bottom like white, brightly luminous milk. When we stepped down to the tap-hole in the furnace, we found it was cooler there, but were deafened by the noise from the tuyeres—the pipes over which the air required for smelting is blown into the furnace. We could no longer hear each other. We could see our lips moving, but couldn't make out a single word. Even a cannon shot would hardly be heard there, I think. The workmen who stay at the furnace unrelieved for a long time must inevitably grow deaf.

"Stepan opened the tap-hole in the furnace gingerly, and a dark crust in it blistered and cracked open. A white-hot, molten mass could be seen in the crack. It swelled, filled the tap-hole, and, driven by the weight of the overlying molten iron and fluxes, began to flow like a fluid, dazzling serpent down the narrow runner made for it in the soft ground, brightly illuminating the dark shed. Sprays of bright sparks went up from this iron milk. Not unlike snowflakes but bigger, the metal sparks took up various shapes. One after another, they rose to the log ceiling, rushed there in glimmering shafts and melted away, as it were, in the heavy darkness. It was hard to break away my eyes from this firework. Finally, the iron filled the moulds and began to cool. At first it turned purple, then took on a bluish tinge, and at last it looked as if ash separated at the top: we could hear a low hissing sound under the ash. The workmen went to separate the pigs from one another".

Alexander S. Serafimovich, another Russian author, also gives a picturesque description of the blast furnace in his story, "At the Works":

"Hastily, the workmen threw ore, coke and flux into the charging car, and the steam engine lifted all this in an instant to the top where its contents were emptied into the mouth of the monster white-hot in the insides. Unwearingly, it swallowed the tons of charge, and the workmen, exhausted with heat, strain and fatigue, kept on filling the insatiable belly, seeing no end of it. Pale and tired, they were black and smoke-covered as if by gun powder, and the sweat running down in rivulets left fanciful patterns on their faces. They couldn't leave the voracious monster for an instant: it commanded constant and strenous attention, it required that people should always be there, without giving them a minute of rest".

Many years have passed, and the blast furnace of today, highly mechanized and automated, resembles its 19th-century predecessor as little as the *Boing-747* does as compared with the *Flyer* built by the Wright brothers. Now it is the height of a 30-storey building and not as tall as 'a good three-storeyed house'. The materials that go into its charge are counted by tens of thousands of tons a day. With the plenty of instruments, recorders and signals on its panels, the control room of a blast furnace looks like a scientific laboratory. The duty of the workmen attending to the furnace have changed beyond recognition, too. They have become highly skilled specialists who work not only (and not so much) with their hands but with their brains.

We will go back to the blast furnace of our time a bit later, and now we leave the manufacture of iron in order to see how pig iron is converted to steel.

Steel, The Chief Metal

The Rebirth of the Ancient Process

The Emperor's Secret Mission — The Spy with a Violin — The Young Mechanic's Griefs — Only a Tale Is Told Fast — Mute Witnesses — The Star Hour of the Former Watchmaker — Shine as the Sun — The Night Visitor

History knows quite a number of legends about stolen secrets. Once they learned how to make silk, glass, porcelain, or special grades of steel, many famous masters, whole guilds and even states wouldn't be in a hurry to part with their know-how. But if there is a secret there will always be someone wishing to get hold of it at any cost and in any way, both honest and dishonest (more often dishonest, of course). It is a fact that as early as the 4th century Emperor Justinian of Byzanthium sent his agents disguised as wondering monks to China, telling them to learn the secret of silk manufacture. The Emperor's mission was a success. That's how industrial espionage was taking shape.

Among the first who ventured to sail in the turbid waters of industrial espionage in the field of metallurgy was Foley, a smith who lived in England in the 18th century. In his search of secrets of the manufacture and treatment of high-quality steel, he disguised as a strolling musician and travelled nearly all over Europe. Bare-footed, clad in rags and with a violin in his hands, he contrived to visit not only castles and taverns in Belgium, Germany, Bohemia, Italy and Spain, but also workshops and smitheries in those countries. The false violinist amassed a real wealth of interesting and useful knowledge. No wonder, therefore, that when he came back to England, his business went uphill, and yesterday's 'tramp' netted a substantial fortune before long.

Before telling another similar story to the reader, it seems worth while recalling the ancient crucible process lost somewhere in the Middle Ages. It fell to Benjamin Huntsman, an English watchmaker, to revive, in 1740, this process once yielding excellent steel for sidearms, instruments, and parts used in many mechanisms.

By that time, what is known as cement steel had spread in many European countries. It was produced by the cementation process in which the carbon content of the metal at its surface was raised by exposing it to the action of some carburizing agent, mostly charcoal. Although cement steel left much to be desired, no other grade of steel was available to replace it.

As a boy, Hunstman showed an unusual aptitude for mechanics. The residents of Doncaster where the young watchmaker had his workshop gladly bought his watches and had their timepieces repaired by Huntsman, and not only watches. Unfortunately, the poor quality of steel would, as often as not, bring to nothing the excellent workmanship of the talented mechanic. This was especially true of clockwork springs and pendulums. Although turned out with a good knowledge of the art and a good deal of diligence, the timepieces would fail before long. Finally, Huntsman felt he was fed up with shame for steel makers, and thought of devising a process for making a high-quality steel from cement steel. To achieve his goal, he moved to Handsworth not far away from Sheffield, the centre of the British metal-making industry. There, Huntsman built a hearth of his design and a clay crucible capable of standing up to a high heat (as high as 1500°C), and got down to experiments.

Month after month and year after year, Huntsman melted small pieces of cement steel under a blanket of crushed green glass used as flux. No records of Huntsman's experiments have survived, but an idea about how much effort he had to put into his undertaking after the watchmaker had turned a metallurgist can be gleaned from the following fact. Many years after Huntsman's death, quite a number of rejected steel ingots were found on the site once occupied by his foundry—he had buried them away from inquisitive eyes. Those mute witnesses of the inventor's many failures were more eloquent than any words in telling that there had been more thorns than roses on his road to success.

Anyhow, the star hour of Benjamin Huntsman, a former watchmaker, came: he had melted in his crucible a steel that could satisfy the most exacting requirements, and has come down into the history of metallurgy as the man who revived the ancient crucible process.

In 1740, Huntsman built in Athercliff, a Sheffield suburb, a small, but the world's first steel works turning out bars of crucible steel. (That year is taken as the year when the crucible process was revived.) However, experiments went on, and the inventor realized before long that the temper of the bars, or their carbon content, could be adjusted at will by adding various amounts of graphite, pig iron, or wrought iron to the heat. Of course, much was done 'by eye', and the workmen determined if the time had come to tap the steel from its shine (it should 'shine as the Sun in a clear day when one is looking at it with an unprotected eye').

Relying on many years' experience, however, Huntsman was able to produce a consistently good steel, homogeneous in structure and free from impurities. He kept his know-how a secret from his competitors who weren't slow in realizing that Huntsman's crucible steel was a good deal better in quality that their cement steel.

Those who wished to 'draw upon' his experience were many, indeed, and it cost Huntsman a lot of effort to protect the secret of his crucible process. Therefore, the most critical steps in the process were carried out at night when it was far more difficult for too inquisitive visitors to steal into the works. Yet it was at night that Samuel Walker, a Sheffield ironmaker, stole the secret of the crucible process.

That's how this happened. Late one evening a beggar came up to the shop where crucible steel was made. Hungry and cold, he asked the workmen, who were getting ready for their job, for their permission to warm himself at the hearth. Although Huntsman had forbidden very strictly to let in any unauthorized persons, the workmen took pity on him and let him sit on a heap of coke at the hearth. Absorbed in their work, they didn't notice when the beggar left the shop. Soon Samuel Walker (it had been Walker who had disguised himself as a beggar) was able to begin the production of crucible steel at his works. That was an indication that the clandestine 'exchange of know-how' had been a success.

Fortunately for Huntsman, the theft of his know-how had not the slightest effect on the activities of his works which soon won world renown. In his declining years, Huntsman not only had a major steel-making business, but also carried a lot of weight with the English industrial and scientific community.

'Steel of Utmost Quality'

Many Centuries' Experience — The Refusal from the Board — The Article in the 'Northern Mail' — 'In the Year Eighteen Eleven' — The Quality 'Bonus' — The Letter of Recommendation — The Success at the World Exhibition

The high quality of crucible steel stimulated its spread in Sweden, Germany, France and some other countries. However, it was an expensive metal, and the crucible process was a slow one. Because of this, cement steel remained in wide use for several decades more.

The cementation process was practiced in Russia for centuries. Russian masters did much to advance and improve the process. Documents have reached our time, telling that in 1820 the Board of Mining and Salt Works, which was part of Russia's Ministry of Finances, received an application from Poliuhov, a merchant, for the privilege of using his process for making cement steel. The application was filed along with specimens of the metal and of the tools made from it.

The Board sent the specimens for tests to St. Petersburg and also inquiries to other works concerned with the making of cement steel and the manufacture and use of tools.

The first to pass his judgement on Poliuhov's steel was the St. Petersburg Mint: "...it is fit for tool-making and strong, and shows a fine and even grain at fracture".

Poliuhov's steel was highly praized by Bitepage, a foreigner which had firmly settled in Russia and had risen high as an engineer and an industrialist. As he wrote, "The specimen of Poliuhov's steel I've received is of the same high quality as one made in England and, as tests have shown, has the same properties as the foreign one". In Bitepage's opinion, the new steel could well replace the steel Russia was buying abroad at a high price to make tools. This was a promise of substantial benefits to the country.

In the words of Vober, Manager of the Schlisselburg Chintz Mill, "Poliuhov's steel is of utmost quality in all respects and can be used to make tools for our mill, being in no way inferior to English or Steirmark steel in tools for turning steel and iron, copper cylinders for chintz-printing, and stamps to engrave the cylinders".

The Board received many more excellent references, laudatory responses, and positive comments on the new steel. The success, it seemed, was around the corner. But not all of the Russian ironmakers thought it was beneficial to give a green light to Poliuhov's steel. Many works, above all those in the Urals, were making steel of a fairly high quality, and their owners weren't interested in the least to see a dangerous competing firm emerging among them.

In August 1823 Poliuhov's request was turned down: "Since the making of steel in its various forms has been brought to perfection at other works in Russia and since its manufacture, already in large quantities constitutes a vital branch of private industry, beneficial to the State as well, The Board of Mining and Salt Works rules that Merchant Poliuhov's request shall be left ungranted". And also, "if granted, the exclusive privilege applied for by Poliuhov of making steel at his works by his process would inevitably bring other similar establishments to a stop, causing damage and ruin to their owners ..., and this runs counter to the interest of the Government itself".

Although Poliuhov's application was left 'ungranted', other Russian metallurgists working at the time developed and commercialized quite a number of other interesting steel-making processes, including cast steel.

Justly ranked among the remarkable iron makers of the first half of the 19th century was Semyon I. Badayev, a former serf, who had learned how to make steel of high quality on his own. His process involved several stages: at first wrought iron was cemented, then the cement bars were melted, and finally the cast steel thus obtained was carburized. To carry out his process, Badayev built a furnace which had a cementation compartment and a crucible compartment.

This is what the newspaper *Northern Mail* for January 14, 1811 wrote about the inventor:

"A certain Semyon Badayev, a serf, made it known to the Government that he had developed a process for making cast steel of utmost quality. The test carried out by Badayev at the St. Petersburg Works of Surgical Instruments under the supervision of a mining official appointed for the purpose fully confirmed his claim. His steel was presented to the Mining Council and from the tests of various things made from it, such as dies, chisels, springs, calipers and drill-bits, it was found to be second to none of English steels.

"The same steel made by Badayev was made into surgical instruments and razors here in Moscow, and the things were found fundamentally good. As the inventor of the new process, Badayev, wishing to make it available for common benefit, put himself at the will of the most gracious Sire and made it known that he was prepared to serve at any place and to open his secret to whomever ordered".

But Badayev was a serf and even the Government, before they could dispose of him as they thought good, had to buy him from his owner. The transaction did take place: "On the tenth of February in the year one thousand eight hundred eleven, I, Vassily, son of Sergey Ragozin, Sub-Lieutenant of the Life Guards' Preobrazhensky Regiment, grant this certificate of freedom to my serf, Semyon, son of Ivan Badayev... I, Ragozin, have been paid, with the permission of His Imperial Majesty and at the expense of the Crown, one thousand eight hundred roubles which I, Ragozin, have received in full at the St. Petersburg Chamber of the Civil Court upon the execution of this certificate of freedom, and he, Badayev, shall, upon entry of the certificate in the Register of State, be free for ever, and neither I, V. Ragozin, nor my inheritors shall in future have any claims on him, Semyon Badayev, or his future descendants, and shall never be involved in anything. Ere now this freed serf of mine, Semyon Badayev, was neither sold or mortgaged by me, nor was he settled upon or left by will to any one." The eighteen hundred roubles mentioned in the transaction included a sizeable 'bonus' for the inventor's talent: the price of an ordinary serf would be a good deal lower.

Badayev was sent to carry on his activities to the Votkinsk
Works in the Urals. An influential official from the Mining
Department gave him a letter of recommendation in which "all
officers and persons to whom this will be of concern" were asked
to give "special treatment to Badayev as a man who holds out
the promise of exceptional benefit to the Works and the State as
a whole", and to contribute "to success in his undertaking". The
letter also described some interesting traits in the inventor's per-
sonality: "Badayev is known to the superior authorities as an
honest and quiet person, and therefore even the minutest com-
plaint on the part of Badayev or any embarrassment from any
one will be looked upon as deeds ill-disposed towards the State's
benefit and the culprits will be asked for an account with all
severity of Law".

At the Votkinsk Works Badayev kept on improving his pro-
cess and carried out other steel-making experiments. His steel
was in high demand in Russia. In 1851, good pieces of news
came from abroad: Badayev's invention had been highly praized
at the World Exhibition in London. But this happened four years
after the death of the talented self-made master.

Searches and Finds

King James I's Grant — Coalbrookdale Again — 'Something Has Happened' —
The Navy Officer's Jacket Is No Longer Needed — The Sudden Death of the
Treasurer — The Vice President's Opinion — Which Way to Go?

As it grew and expanded, industry needed ever greater quantities
of steel, but its supply was obviously short although metallur-
gists in all countries had long been looking for ways and means
of meeting the mounting demand. The European monarchs in-
terested in the growth of metallurgy supported the search for new
processes in every way. As early as 1617, King James I of England
granted two London artisans a patent. Among other things, it
stated that a great need was felt in England, Ireland and the
Dominions for steel to make armour and arms, and also tools for
carpenters, masons and other trades. It was stressed that the
output of steel in the Dominions lagged heavily behind the de-
mand. Aware of the fact that his 'dear subjects' would be brought
to buy steel from overseas in order to satisfy their needs, the
king said he wished that steel should be made within his kingdom.

By the mid-18th century, many countries were producing sizeable quantities of pig iron in their blast furnaces, but their bloomeries were unable to process all of their pig iron into wrought iron. Also the bloomeries needed charcoal—a scarce fuel happily replaced with coke in the blast furnaces. Quite logically, the metallurgists had been working in this direction.

Among those who were the first to find an acceptable solution of the problem were the brothers Thomas and George Cranege, workmen in the same town of Coalbrookdale where Abraham Darby, Jr. had successfully used coke in his blast furnace three decades before. The essence of the process that the Cranege brothers proposed in 1766 was this. Pig iron was to be converted to malleable iron in a raw coal-fired furnace so that the metal was 'divided from the touch of the fuel' (by what has come to be known as the bridge) and was heated and turned to a pasty mass by the heat 'reverberated' (that is, reflected) from the arch of the furnace, because of which the iron would pick up much less sulphur than in the case of the bloomery process. To provide a better contact between the pig iron and the slag and, in consequence, to assure that as much carbon was burned out as possible, the molten metal was to be agitated with an iron bar.

The Cranege brothers disclosed their idea to Richard Reynolds, Manager of the Iron Works. As Reynold believed, something of special importance for the future had happened. As he wrote in a letter, a certain Thomas Cranege, a former workman at the Bridgeport Smithery, and his brother George approached him. While discussing the smelting of bar iron with charcoal, they told Reynolds that it was possible to make good malleable iron by the use of raw coal alone for fuel. Reynolds objected by saying that this couldn't be done because even charcoal entailed noticeable inconveniences as it carried alkaline salts which combined with the sulphur of the iron and gave it red brittleness, and that raw coal since it contained salts, sulphur and many other impurities would be far more inconvenient than charcoal. The Cranege brothers answered they had made observations and had thought upon the subject and were of the opinion that pig iron was turned to bar iron by the force of high heat and that they would be only too glad to demonstrate that this could be done by the use of raw coal. Reynolds gave his consent but, as he remarked, he was greatly in doubt as to the success of their experiment.

Several weeks had passed and Reynolds had nearly forgotten their conversation when, all of a sudden, Thomas Cranege came from Bridgeport, accompanied by his brother, George. They built a small hearth of their own design and, after several tests, built a furnace in which the iron was separated from 'the touch of the fuel' and was solely heated by the reflected heat. Before long, a success came so overwhelming that it exceeded all expectations. As Reynolds noted in his letter, the brothers used a very hard iron and rendered it soft and pliable by their method. The Works Manager was sure the invention was extremely important and was determined to solicit for a patent.

As Reynolds summed up, the discovery consisted in that a reverberatory furnace should be built in a special way and receive a charge of iron pigs to be converted by the heat of raw coal to an excellent and malleable iron; removed from the furnace while red-hot, it could be hammered to bars of various sizes and shapes as the workmen might wish.

Soon the Cranege brothers were granted a patent for their process.

It would seem that the problem of converting pig iron to malleable iron had been solved and that the Cranege brothers could reap the fruits of their happy idea. However, the history of technology has known many cases where the 'seeds' were planted by one person and the 'fruits' were reaped by an entirely different man. As the saying goes, two minds are better than one, but the two brothers' bright minds proved not enough not only to devise a new, promising iron-making process, but also to make it routine practice at iron works. The process they had developed never left the limits of Coalbrookdale, and the Cranege brothers died unknown to the outside world.

But the process caught on and kept developing. One of its proponents was Henry Cort, an English businessman and works-owner. He had served in the Royal Navy until the age of thirty-five, but had retired in 1775 and bought a small estate. Cort had long been interested in iron making, so he built on his estate a smithery which soon grew into a small iron works. There the owner changed from his Navy officer's jacket into a leather apron and became utterly engrossed in iron-making experiments.

After several years' work, Cort fell upon the idea of hollowing out the bottom of the furnace so as to contain the metal in the molten state. Then by agitating this "puddle" or bath of metal with an iron bar or paddle, he was able to produce wrought iron. In 1784 he was granted a patent for this puddling process. A year before he had taken out a patent for a squeezer—a set of rolls intended to squeeze slag out of the "ball" and to compact the metal. Now Cort went further than that: the new patent envisaged the rolling of the squeezed ball into what is technically known as muck bars. His muck, or puddle, mill consisted of a single stand or set of rolls which had grooves of suitable shape.

Cort also did much to promote the practical use of the puddling process. Therefore, he is usually credited with the discovery of the puddling process and not the Cranege brothers. Is it just?

As some British historians of technology note, there is no consensus on Henry Cort's contribution to the progress of metallurgy. Some look upon him as a trail-blazer whose discoveries have been of great value. Others treat him simply as a plagiarist who exploited the ideas of other inventors to his own advantage. One thing is unquestionable: puddling became a routine practice at iron works only in the wake of Henry Cort's effort.

It is true, though, that the spread of the process was to a certain degree promoted by a chance concurrence of circumstances which had grave consequences for Cort. Eager to set his process going as fast as he could, Cort borrowed a large sum of money from a friend of his, who was the Treasurer of the War Ministry. Unfortunately, the man soon died and, since rumours were flying that he had embezzled a whole fortune at the Crown's expense, the Treasury set out investigating his financial activities. Cort was ordered to pay his debt at once, but all of his capital was invested in the undertaking which had not yet come to bring in any income. By the Court's ruling, Cort's property was sold by auction, including his patents. This was a severe punishment, but metallurgists in England and then in other countries obtained an opportunity to use and improve the puddling process at many iron works. And who knows? If this hadn't happened, Cort's name might have never won so wide a renown.

The puddling process, relieving iron making of its charcoal bond, came as a big shot in the arm for English industry: the iron works stepped up their scale of production and, as a consequence, the country's iron output grew substantially. While England had to buy over forty-eight thousand tons of iron from Russia as early as the late 18th century, the figure dropped to one-tenth in the early 19th century.

Soon other countries followed England's suit in building puddling furnaces. In 1795, a team of English metallurgists headed by Master Walker was invited to the Lugansk Iron Works in Russia. Their task was to set up the manufacture of pig iron with raw coal as fuel and its conversion to malleable iron in reverberatory (puddling) furnaces.

At the time, the Vice President of the Mining Board (set up by Czar Peter the Great in 1719 to supervise the Russian mining industry) was A. A. Musin-Pushkin, a prominent chemist and mineralogist, a man of progressive views, who did much to advance metallurgy in Russia. He saw it important to publicise the puddling process on the largest scale possible. In his article published in the *Journal of the Free Economic Society*, the Vice-President wrote: "Instead of turning their pig iron into malleable iron in the bloomery, the English have for more than a decade now been doing this job in reverberatory furnaces in which some have even successfully tried to convert the ore directly into malleable iron, and also producing cast steel adaptable to forging. I have had an occasion to hear from Walker, a dexterous English foundry-man and steel maker, an explanation of how this is done, and believe it worthy of attention for Russia. I think it would be well-advised for any ironmaster to receive at least a superficial knowledge about the process and plant". The article then went on to describe the puddling process and the reverberatory furnace. As the Vice President concluded, "The benefits of this method are so much tangible that it seems unnecessary to expatiate on the subject. The iron is nearly always produced highly consistent in both appearance and properties and at a large profit because of the smaller burning loss. In short, the process will, in my opinion, greatly affect not only the iron works but all of the foundry practice in general".

However, the Russian iron works were reluctant to adopt the new process for many years, although there were isolated attempts to use this method undoubtedly highly advanced for its time. It wasn't until the 1830s or 40s that puddling came to be practiced to some extent at the Votkinsk, Vyksa, Chermoz and some other works. But even then and later, when the manufacture of puddle iron had reached sizeable proportion, the fuel for the reverberatory furnaces was as a rule charcoal or, simply, firewood because in a country so rich in woods such a fuel was cheaper than coal, and also because there was nobody yet to take care of the Ural forests.

Puddling played an important role in the development of iron making. In the first half of the 19th century the iron produced by the puddling process was the principal material of construction for mechanical engineering, building construction, and railways. However the process was far from perfection. Using heavy iron bars, or paddles, the workmen stirred the huge puddle of pasty molten metal by hand until the time came for what is known as balling—the metal was formed into large balls each fifty to eighty kilograms in weight, and these were drawn (during a 'drawing' operation) from the furnace to be worked into rough blooms with a hammer, an operation called shingling. As Professor John Percy, a prominent 19th-century English metallurgist, noted, there wasn't any other manufacture where man's muscular force was subjected to so strenous effort and in so exhausting an environment. It is therefore no wonder that the puddlers didn't want their children to learn their trade which, incidentally, made a man no longer able to go on with it at the age of forty-five or fifty.

Of course, the owners didn't think of their workmen, but they were worried about the fact that the process was a slow one and the metal would sometimes fall short of the now more rigorous requirements of technology.

Anyhow, that's how matters stood in iron making in the mid-19th century: the puddling process and, the less so, the bloomery process, no longer satisfied anyone because they were slow, labour consuming, and producing a low-quality metal, while the crucible process, although capable of making a good quality of steel, was expensive and could be used on a limited scale.

Metal-makers kept on looking both for new processes to make cast steel on a large scale, and for ways and means of improving its quality. Important milestones in this effort were justly the works of Pavel P. Anosov and Pavel M. Obuhov, outstanding Russian metallurgists, scientists and engineers of the 19th century.

The Secret of Oriental Steel

The Miraculous Patterns — Well into the Small Hours of Day — Surprise for Alexander the Great — Thirty Names — The Sword or the Elephant — Faraday Makes an Error — The Anthem to Iron — 'An Ocean to Cross' — Flowers and Leaves — 'Czar's Appreciation' — World Renown

While the 18th century was destined to revive the long forgotten crucible process, it fell to the 19th century, its successor, to re-discover another ancient secret lost in centuries—the art of making Oriental sword steel the most famous grade of which has always been known as Damascus steel or damascene. The task which had attracted metallurgists in many countries for centuries was achieved in the 1830s by Pavel P. Anosov of Russia.

An orphan from his early childhood, Anosov was put in the St. Petersburg Mining Cadet Corps at the expense of the Crown in 1810. Later, he would more than pay back the money spent by the Czar's Treasury for his instruction through his valuable contributions to Russian metallurgy.

Among its exhibits, the Corps's Museum had ancient damascene swords. The inquisitive cadet spent many hours in the Museum, closely looking at the beautiful patterns on the metal, which looked like ripples of water, strands of silk, or bunches of grapes. The patterns hadn't, as the boy knew, been applied by man's hand—they had appeared of their own accord when the sword was hammered. The boy also knew that the most remarkable thing about this wonderful metal was not the beauty of its patterns, which were solely a sort of 'identity card', but the amazing ability of damascene swords and sabres to cut other metals easily without losing any of their sharpness. A damascene blade could be bent into an arc, but it would, singing like a string, become straight again as soon as it was let free.

The enchanted boy would stand for hours on end in front of the show-cases displaying specimens of Oriental sword steel. How could one possibly disclose the secret of the miraculous metal? It must have been in those hours that the young Anosov decided that he would, sometime in the future, learn the art of the ancient masters who had known how to make this wonder of steel. But now he had many years of instruction before him.

Sometimes little Pavel visited the Museum late at night when everybody had long been asleep. Glittering in the shaky flame of a candle, the mysterious patterns seemed to come to life, and the boy was unable to draw his eyes away. It was especially hard for him to leave the room in those minutes.

Once the young cadet stayed in an armchair next to the damascene show-case well into the small hours of the day and, exhausted by day studies and drills, fell asleep with a burning candle in his hand. Early in the morning he was found there by the inspector of the classes. Collecting the stub of the candle and the solidified drops of wax as 'material evidence' (to use the court's parlance), the inspector went hurriedly to A. F. Deryabin, Director of the Corps, to report the crime. As a lesson for the other cadets, the inspector insisted that the poor boy should be punished with rods. However the director, who was a kind man and liked his cadets as a father would like his sons, was able to look into the soul of the young offender. "Why should we punish him?", he retorted. "His only crime is his desire to find an answer to a problem, and if he finds it, this would do credit to our country". The director didn't suspend a bit how prophetic his words were: years would pass, and this shy little boy standing in front of him, with his head turned down, would be a great honour to Russia—he would discover the secret of ancient Oriental steel wrapped in a veil of mystery.

Enraptured, Anosov read all the books on metallurgy that the Corps' library had. He learned that it was customary to regard India as the country of origin for sword steel, where high-quality steel had been made nearly fifteen hundred years before Christ. He read a legend telling how, in the 4th century B.C., the Indian King Porus had courageously fought the armies led by Alexander the Great at the river Hydaspes. But the odds were in favour of the Macedonians, they defeated the Indians, and King Porus was taken prisoner. But the Macedonians were greatly surprised when they saw not a single dent or scratch on the Indian King's armour although he had been in the very midst of the battle. The King's armour which had withstood a great many sabre blows and a veritable hail of enemy arrows was made of an unusually strong metal for which Indian masters were so famous.

As we know today, small ingots of high-quality Wootz steel which looked like flat cookies were made in India well before Christ and were carried by merchants to many countries in the Middle and Far Fast to be made by their armourers into excellent blades. For the buyer to see the merchandise to advantage, the merchant would show him a Wootz steel cake cut in halves: from the look of the cut a discerning customer could at once see how fine-grained the structure of the metal was.

Moving to other countries the Wootz steel of India would usually take on other, local names: the famous Oriental steel has a total of about thirty names. The most common ones are 'damask', 'damaskene' or 'damascene', meaning 'a steel of or as of Damascus', although it could be made elsewhere, not necessarily in Damascus.

Side arms made of damask were valued high by all nations who were good judges of the metal. In India, for example, an eager customer would readily give an elephant for a damask sword, and elephants were always at a high price there.

Europeans came to know damask side-arms well after Oriental nations. Although some armourers learned how to make swords, sabres and daggers from the damaskene brought in from abroad, they failed in disclosing the secret of its manufacture. Centuries passed one after another, but the secret of damaskene lost in the Orient as well remained an unresolvable riddle. It gave rise to an especially great interest after Napoleon had conquered Egypt from where he brought a huge number of invaluable damaskene arms.

Early in the 19th century an English traveller bought several Wootz ingots in India. When he came back home, he presented them to the London Royal Society. The Wootz ingots intrigued many scientists, among them Michael Faraday, a highly distinguished chemist and natural philosopher. After a careful chemical analysis, he found that the metal carried some aluminium. There was no way of saying if the aluminium had found its way into the Wootz steel by chance or it had been added on purpose. But Faraday thought—and quite wrongly—that the key to the mystery was aluminium, a very expensive metal at the time. The scientist made an amount of steel carrying some aluminium and hammered it into a blade. To his great joy, the metal did show the wavy patterns usually found on damaskene. But his joy was short-lived: the patterns were soon found to be the only good thing about the blade. When put to work, the blade proved inferior in some respects even to ordinary blades made of good English steel.

Faraday went on with his experiments, using platinum, gold and silver as alloying additions to iron, but even these noble metals were unable to confer the miraculous properties of damaskene upon the steel. Failing to achieve anything, Faraday gave up on his metallurgical experiments and took to electromagnetism and electrolysis where he won himself world renown. As futile were the attempts to produce damaskene in Germany, Sweden, and France.

It was in those years that Pavel Anosov became concerned with many centuries' mystery. In 1817 he graduated from the Mining Corps with honours. He didn't hesitate which field of metal-making to choose for his future work: all thoughts of his were associated with iron. He wrote in his graduation thesis: "Nature seems to have foreseen that mankind will need iron and has disseminated it in incomparably greater quantities than all other metals: there is not a single country lacking the signs of iron, and there is not a single walk of life where the need for iron isn't felt".

Anosov was sent to work in the Zlatoust Mining District, the Urals. The district included several iron and steel works the most important of which was the Zlatoust Works incorporating an arms factory. It was there that the young metallurgist began, in the modest capacity of an 'errand' technician, his career which later led him to the summit of glory.

Two years later the talented engineer was appointed superviser of one of the arms factory's shops, and in six years more he was promoted to the position of its manager. Anosov sought to turn iron-making from an art into an exact science. For in his days even the best masters who knew how to make excellent steel had nothing to draw upon except their experience or the experience of their predecessors who may have passed their know-how onto their successors. But they didn't know what actually happened in the metal while it was being smelted or worked, so they weren't able to purposefully guide the metal-making process and couldn't therefore make improvements in the manufacture of iron and steel at will.

Exactly this was the object of his long and pains-taking studies and the purpose of his life. Later, when Anosov had something to show for his effort in the field he had chosen and was a widely known metallurgist, he wrote, recalling the start of his career, that his long scientific search now appeared to him as "an ocean that has taken him years to cross, without a chance of pulling in to the shore, while exposed to many vagaries".

One of the tasks facing Anosov was to develop a process by which high-quality cast steel could be made in crucibles—this was in fact the first step on the road towards unravelling the mystery of damaskene.

His experiments needed above all inexpensive crucibles of high quality. Anosov flatly turned down the crucibles brought in from abroad: they cost Russia a pretty penny and couldn't be used in the large-scale production of steel for that reason alone. He was sure he could find the clay he needed here, in the Ural Mountains so rich in all kinds of ores, minerals and rocks. But a good deal of time was to pass before the material he needed was found. Experiments followed one after another, and one failure would lead to just another. Anosov had walked tens of miles around Zlatoust before he found what he was after. The crucibles he made could stand up to high temperatures for a long time and their cost was a mere fraction of that of the foreign-made crucibles. The time had come to think of how to make steel in them.

As we have learned, Badayev combined the cementation compartment and the crucible compartment in one furnace where the two steps were carried out in turn. Anosov went further than that by combining cementation (carburizing) and melting in the same crucible. Also, counter to the prevalent notion that for carburizing the iron must be in contact with powdered solid carbon, he justly thought it possible to use the carbon of the furnace gases, rather than solid carbon, that is, coal, in order to saturate the iron. This offered a possibility to control the degree of carburization (the carbon content of the metal): for that purpose it was enough just to put down the lid of the crucible holding the molten metal at the right moment, thus isolating it 'from the touch' of the furnace atmosphere. Through these innovations, Anosov was able not only to make high-quality steel but also to speed up the process many times. He tried charges varying in the relative amounts of wrought iron and pig iron, and finally could produce steel from pig iron alone. That was a major step forward in the metallurgy of iron.

But it wasn't enough for Anosov to produce simply a high-quality cast steel: as before, he was after damaskene, and he was firmly bent on unravelling its secret. As Faraday had done before him, Anosov began with the additions made to iron on the assumption that they were responsible for the unique properties and inimitable patterns of damask steel. He made thousands of experiments, using silicon, manganese, aluminium, titanium, gold, and platinum. Finally the young engineer came to a firm belief that none of them could turn ordinary steel to damaskene: it contained practically nothing else except for iron and carbon, and its wavy patterns owed their origin to the crystalline structure of the metal.

Nevertheless his effort was of utmost importance: during his experiments Anosov had gathered a detailed knowledge about the effect of many chemical elements on the properties of iron—in fact, he founded the metallurgy of alloy steels.

When he had found that damaskene was merely an alloy of iron and carbon, Anosov soon concluded—and very justly—that damask steel owed its magic properties to the ratio in which the two components were present and, as the metallurgist wrote himself, "to the manner in which the carbon unites itself with the iron", that is, to the unusual structure which is typical of damaskene and sets it apart from ordinary steel. It was therefore necessary to learn the subtle points that were responsible for the required structure of the metal. Couldn't it be that everything hinged on the state in which the carbon had resided before it formed its union with the iron?

Anosov investigated how the structure of steel could be affected by carbon produced from vegetable and animal materials. He used literally everything in his experiments: wood, soot, flowers, leaves, horns, ivory, millet, and flour, but the metal thus produced wasn't a bit like damaskene.

Well, it only meant that the key to the mystery should be looked for somewhere else. Now Anosov used carbon of only mineral origin—pure graphite found in the mountains a few tens of miles away from the works.

One heat followed after another and still another. Changes were made in the composition of the charge, the temperature of the molten metal, the amount of slag, and the duration of the process—all that are known as the process variables today. Every change was meticulously recorded in a 'Log of Experiments'. To investigate the structure of the metal, Anosov used in 1831—for the first time in metallurgical practice—a microscope, thus laying the first stone in the foundation of metallographic analysis which is a major tool in the study of metals and alloys nowadays.

After many months and years of strenuous effort Anosov made the final choice of the components for the charge: pure iron ore and especially pure graphite, their relative amounts, the only and correct rate of cooling, and all the minutest details that, when acting together, would produce damaskene. One fine day (it would be a fine day to Anosov all the same, even if it was raining cats and dogs or a hurricain was blowing) the long coveted damaskene pattern was seen to appear. And then the first damaskene blade was made. This happened in 1833. As Anosov wrote, "The strip of damaskene could be bent without any damage and rang with a clear and high-pitched note. Its polished lip could chop up the best English chisels". The blade could easily cut not only nails and large animal bones but also a fine, gossamer kerchief sent flying in the air. That was the best proof of the metal's quality. There could be no doubt: damaskene of excellent quality had been produced, and the mystery of many centuries had been unravelled.

Soon Anosov, already promoted to Chief of the Mining District, organized a large-scale manufacture of damaskene, and blades carrying the trade mark of the Zlatoust Arms Factory became farfamed. In 1837, two damaskene sabres and a Cherkess sword, made in the Urals, were sent to St. Petersburg as a gift to the Czar. The Head of the Corps of Mining Engineers conveyed to Anosov "the Czar's appreciation of the first specimens of Russian damaskene presented to his Majesty". Two years later arms and other products made of Ural damaskene were widely demonstrated in St. Petersburg. The experts who tested Anosov's steel found, for example, that "a razor of good Ural damaskene, when properly made, can shave at least twice as many beards than the best English one".

To sum up many years' studies, Anosov published in 1841 his fundamental work, "On Damaskene", which has become a classic publication on the metallurgy of high-quality steels and has come down into the world's golden treasury of books on metallurgy. It was translated into German, French and other languages at once. Anosov's work was estimated at its true worth by many advanced members of the Russian technical community. There was a body of opinion among the leading scientists who believed that Anosov's "On Damaskene" was the right candidate for the Demidov Prize, an award conferred by the Russian Academy of Sciences every year 'for best publications in various fields in Russia'. As one of the reviewing peers noted, "Anosov has been able to produce a steel possessing all the qualities that are highly appreciated in Oriental damaskene and exceed all grades of European steel which are extremely soft before quenching but become much harder than the best qualities of English steel after quenching".

Unfortunately, as had happened more than once in the Imperial Academy of Sciences, the award went to someone whose works and name soon fell into oblivion, and not to Anosov. Some influential 'savants' thought there was nothing special about Anosov's works. Many experts outside Russia were, however, of a different opinion. One of them was the English scientist R. Murchison who visited the Zlatoust Works and wrote that it was highly doubtful that there was, in the world, another factory that could compete with Zlatoust in the making of arms. He also added that the exquisite things of damaskene he had received from Anosov fully justified the praises meted out to him. These articles and the steel tray richly decorated with inlaid gold, sent as gifts to the authorities of the Russian Mining Board excited general admiration in England.

During his final years in the Urals, Anosov stood behind the attempts to make field guns of cast steel. This important engineering idea was to be followed up later by other Russian metallurgists.

Visitors to Zlatoust can see a beautiful monument: standing on a granite pedestal is the figure of an officer of the Mining Engineers Corps, holding in his hands a blade bent into an arch. This monument has been set up in memory of the Russian metallurgist Pavel P. Anosov. He seems to be about to let go of the blade so it could straighten itself with a springy ring.

The Gold Medal to a Steel Field Gun

And No Troubles — The Needs of the Russian Army — The Project Finds Support — The Czar and the Gun — On the Bank of the Neva — The Way to Truth — The Star Grows Dark — On the Way Back — The Knight and the Salamander

After Anosov's departure from Zlatoust in 1847 (he spent the closing years of his life as Chief Administrator of the Altai Iron Works and Civic Governor of Tomsk), there was a marked cut-back on the manufacture of crucible steel in the Urals. Resort was again made to the imported English and German steel which carried a higher price but came ready for use, relieving the works owners of what they thought was unnecessary trouble.

The crucible process saw a kind of revival in the Urals in the mid-1850s, which was related to Pavel M. Obuhov, a prominent Russian metallurgist.

In 1843 he graduated with honours like Anosov from the Institute of the Mining Engineers Corps (as the St. Petersburg Mining Cadet Corps was re-named in 1833) and was sent to the Urals. Two years later he was appointed supervisor of the Serebryansk Works and soon was sent abroad where he stayed two years learning the know-how of iron and steel manufacture in Germany and Belgium.

Back home in 1848, Obuhov served first at the Kuvshinsk and then at the Yugovsk Works. Several years more passed, and he was appointed Manager of the Zlatoust Arms Factory headed for many years before him by Anosov. It was there that Obuhov set about to realize his long coveted project he had first thought of during his visits to European works: he wished to organize the large-scale manufacture of cast steel in Russia. Before this could be done, however, the crucible process which had fallen into decay had to be revived.

Russia was waging the Crimean War, and its armies badly needed arms, shells, and armour. Obuhov's idea was to cast steel field guns instead of the antiquated iron and bronze pieces.

Realizing how critical and formidable the task facing him was, he carried out a host of experiments until he was sure that his steel smelted in crucibles by the new process wasn't inferior to that from Germany or England but was in some respects even better. As an expert who visited the Zlatoust Arms Factory at the time wrote, "Obuhov's steel is easy to hammer without developing even the minutest cracks, either longitudinal or transversal, and loses none of its initial properties in the process. This is one of its virtues".

At first Obuhov used his steel to make cuirasses and rifle barrels. The cuirasses were much lighter in weight than their predecessors and no less strong, and the Obuhov rifles could stand twice as many shots as those made of the famous Krupp steel. As a report from Zlatoust to St. Petersburg noted, "Many hunters in Zlatoust have now rifles which are made of Captain Obuhov's steel. They are highly accurate in firing and strong".

The Russian Army needed cuirasses and rifles, but it was in a far greater need of artillery. Aware of this, Obuhov wrote in one of his reports to the Chief Administrator of the Zlatoust Works in 1855: "It would be convenient to make field guns of cast steel, and they would be much lighter in weight, less expensive and stronger that those made of copper..."

Two years later he was granted the privilege of making cast steel on a mass scale by the process he had developed, and reported to the government the plans and specifications of a works to make steel field guns. At the time, Krupp's works in Germany were already using crucible steel to make guns of a fairly large caliber, weighing sometimes over twelve tons apiece. Many countries, including Russia, were buying them. With gun manufacture of its own, the country would be able to put an end to its dependence on a foreign supplier and to the need to pay a good deal of money to German manufacturers.

Obuhov's project found, therefore, support among many highly placed officials at the War Ministry who had learned a good lesson from Russia's defeat in the Crimean War and realized how important it was to re-arm the Russian Army. The permission to build the works was given, and construction was soon in full swing in Zlatoust. In early 1860, the new factory named the Prince Mihail Steel Gun Works went into operation and soon turned out its first products—four small gun barrels. They were despatched to St. Petersburg for tests which were a much greater success than had been expected: after several thousand shots the guns not only remained intact, wh ch was a major accomplishment in itself, but wouldn't lose none of their firing accuracy.

Czar Alexander II himself was present at the tests. Before they began, as the contemporaries recalled later, he asked Obuhov:

"Are you sure your gun won't burst?" A little embarassed at first, the officer answered firmly: "I'm, Your Majesty!" After a thousand shots or more, the Czar asked again: "Are you sure the next shot won't burst the gun?" The governmental commission included a general who sympathized with Obuhov and was his guardian in the high places; on top of that he was known for his cheerful disposition. Before Obuhov could answer, the general, with a mischevious smile on his lips, asked His Majesty's permission for himself and the gun's maker to sit over the gun and to go on with the test. Of course, they didn't have to do as the general suggested, but the outcome of the test showed they wouldn't have risked a bit if they had done so.

Obuhov's steel passed the test with flying colours, it might be said. The Artillery Committee went so far in their praise as to write in their findings: "Obuhov's cast steel is excellent, indeed, and his gun has admirably passed firing tests with far stronger charges than are ordinarily used. The toughness and ductility of the steel are such that the gun has withstood four thousand shots without any tendency to burst, and the metal has lost none of its quality. The gun delivered by Obuhov is in no way inferior to Krupp's guns and it remains only to wish that similar guns could be made in large numbers".

Two years later the now famous Obuhov gun was demonstrated at the World Exhibition in London and was awarded a gold medal. The gun is still intact and can be seen in the Artillery Museum in Leningrad, USSR. Its carriage bears an inscription which reads: "Cast in 1860 at the Prince Mihail Works from Obuhov steel. Fired over four thousand shots".

The Czar was lavish in pouring honours on Obuhov: the metallurgist was promoted to the rank of general and appointed Chief Administrator of the Zlatoust Mining District. Under his guidance, the manufacture of cast steel and guns in the Urals kept on expanding. But he remained there for a short time: since the Russian army needed heavy steel guns for fortresses and large warships, it was decreed to build two new works for their manufacture, one in St. Petersburg and the other in the city of Perm. In 1863 Obuhov moved to the capital to head the construction of what later was named the Obuhov Works. It took two full years to erect buildings and to install crucibles, steam hammers, machines and other pieces of plant. Highly skilled steel-makers and smiths came from Zlatoust in the Urals, and some specialists were invited from abroad.

In the spring of 1864 the first large heat was tapped at the Obuhov Works, and the metal was cast into seven small billets for gun barrels. A bit later, a large billet tipping the scales at twelve tons and intended for a heavy gun was cast. Everything seemed to go on well, but troubles began to popping up all of a sudden: in contrast to the first light guns made at the Prince Mihail Factory, not all of the heavy guns made in quantity at the Obuhov Works had high mechanical properties. Some of the barrels were able to stand up to thousands of shots while others cast of the same steel would blow up on the proving ground when a test had just begun. Why was it that the metal behaved so differently?

Couldn't it be that the steel was of poor quality and one should only wonder why many guns still served faithfully for a long time? No, as many chemical analyses and mechanical tests showed, the steel met all the stringent requirements as to composition and properties.

Obuhov realized that he could only get to the heart of the matter through pains-taking and in-depth scientific research, and for this he needed money. But his star was growing dark, and he could hardly expect to receive any financial aid from the military authorities. Indeed, talk started in the governmental circles that the manufacture of steel guns in Russia should be closed down and orders for ordnance should again be placed with foreign firms.

Nevertheless, the management of the Obuhov Works was able, in 1866, to invite a group of scientists to investigate the causes of failures, to set right the manufacturing process, and to assure the required quality of guns and other products, which they soon did. (We will go back to this 'miraculous healing' of the Obuhov Works a bit later, as the research done there had heavy impact on the progress of metallurgy the world over.) But Obuhov himself had by that time all but retired: broken by failures, he fell ill and went abroad for a cure in 1868. On his way back, this remarkable metallurgist and innovator who had perfected the large-crucible process of steel making and had organized the large-scale production of steel in Russia, died in a Moldavian village when the year 1869 was just a few hours old.

An Austrian expert who visited the Russian iron and steel works on the invitation of the Russian government in 1870 was greatly impressed by what he saw: "Indeed, I was pleasantly surprised to see, both at an exhibition in St. Petersburg and at various plants, all the latest advances and innovations in iron making already at work, sometimes so improved that they may as well be taken as models for other nations. For example, the manufacture of cast steel in large quantities and its use in the making of steel guns, tyres, and other products, with all the necessary mechanical devices, at the Obuhov Works near St. Petersburg and at the Perm Steel Works may be ranked as equals with the famous Krupp Stahlwerke in Essen".

The crucible process played an important role in the iron and steel industry in Russia for several decades. Guns and shells, rifles and armoured carriages, tools and other critical products were made of steel smelted in crucible furnaces. It is no chance that the best grades of crucible steel in Russia were given the sonorous names of Success, Victory, Warrior, Holy Mountain, Champion, Salamander, and Might.

The crucible process to which damaskene owes its re-birth and which had a vital bearing on the first steps of cast steel manufacture has left a noticeable trace in the history of Russian and world metallurgy. But it wasn't the crucible that was destined to bring about a veritable breakthrough in steel making—this was to be done by the Bessemer converter, the open-hearth furnace, and the electric furnace—all of them invented in the latter half of the 19th century. Even today, they support, like the three biblical whales, all of steel manufacture.

The Three Whales

'Veni, Vidi, Vici'

In the Heat of the Crimean War — 'To Build a Good Name and Wealth' — Bessemer's 'Sheer Ignorance' — The Eruption of the 'Volcano' — 'There Will Be Something to Laugh at' — 'To Goal for Manslaughter' — Millions and Millions

The history of technology knows quite a number of bright personalities, and one of them was, quite justly, Henry Bessemer, the illustrous English inventor of the 19th century. His interests went very wide indeed, and he was granted over a hundred patents in various fields of technology during his life. But, undoubtedly, the most remarkable invention which brought Bessemer world fame was related to metallurgy or, to be more specific, to steel making.

By the age of forty Bessemer had built himself quite a name as an inventor, but he was entirely indifferent to steel making. So when he invented a large artillery shell of a special design, he could hardly expect that the shell was destined to bring on a sharp turn in his engineering thinking.

What happened then?

At the end of 1854 when the Crimean War was at its height, the shell was being tested on the Vincennes proving ground in France. Captain C. Minié, who headed the expert commission (incidentally, he was the inventor of the rifle-barelled gun), noted that little remained to be done: it wouldn't be a bad idea to build a gun which could fire such heavy shells as well.

Bessemer set about to devise the new gun. Obviously, he was born with a silver spoon in his mouth: everything he undertook would usually be a success. It was no different this time, either, although he invented a thing quite different from a gun.

The inventor realized that the first thing to do was to find a suitable material which would be able to stand up to all the strains and stresses arising when a large-caliber shell was fired. Cast iron and bronze ordinarily used for the purpose at the time didn't suit Bessemer, and he decided to try and obtain a better grade of cast iron. As he wrote later, he hadn't the slightest idea how to go about this new and important problem, but the very fact that he was to invent something was enough to spur him. He had before him a chance to build a good name and wealth, and he ran the only risk of wasting his time and effort, should the attempt end in a failure.

At first Bessemer used a small hearth, then a puddle furnace. As the inventor recalled later, a noticeable event took place during one of his experiments: he saw that several lumps of pig iron on one side of the bath hadn't melted although the temperature in the furnace was very high. Bessemer turned on a stronger blast to step up the combustion. But when, a half hour later, he looked into the peep-hole he saw the lumps hadn't melted all the same. As he tried to push the lumps into the puddle with an iron bar, the inventor noticed that those weren't solid lumps of pig iron but the remaining thin crusts of decarburized iron. This was an indication that atmospheric air could completely decarburize pig iron, thus turning it to malleable iron without resort to puddling or any other manipulations. On second thoughts Bessemer concluded that if he had means of bringing air in intimate contact with a sufficiently large area of molten iron, this alone would quickly turn it to malleable iron.

What events take place in the molten metal when it is brought in contact with air? As Bessemer himself believed, the carbon of pig iron, when exposed to a white heat, couldn't but combine with oxygen and couldn't but burn. It followed then, as he thought, that it would be enough to bring the carbon and the oxygen in contact so that large amounts of them were involved in the interaction—this would produce a temperature not attainable in the largest of furnaces. Although Bessemer was wrong in believing that the largest amount of heat was liberated, on burning, by carbon (this is done by silicon as we know it today), his idea was basically correct: for molten pig iron to part with its carbon, it must be blown with air.

This brilliant idea which brought about a veritable revolution in steel making seemed preposterous, to say the least, to many at the time. The first to show his scepticism was the foundryman Bessemer had engaged to make trial heats in the inventor's shop. When Bessemer told the foundryman he wished to blow the molten metal with cold air in order to raise its temperature, the man's face took up an expression the inventor remembered all his life. It was a mixture of surprise and pity for Bessemer's "sheer ignorance". "The metal will soon turn into a solid boulder", the master said without a shadow of doubt. How great his surprise was when, after the blow, a dazzling stream of metal poured down the runner, into a ladle, and then into a mould. As Bessemer wrote later, he wasn't able to describe what he felt when he saw the white-hot mass slowly rising in the mould. That was the first large ingot of cast steel that the human eye had ever seen.

In 1856 Bessemer took out a patent for the most important invention of his life—the conversion of pig iron into steel by blowing air under pressure through a bath of molten metal. He discovered, as he summed up his invention, that if atmospheric air or oxygen was admitted into the molten metal in a sufficient amount, it would bring about a strong combustion of metal particles and maintain or even raise the temperature to such an extent that the metal would remain liquid as it changed from pig iron to steel or malleable iron without the use of fuel.

At first Bessemer used a small vessel to blow molten pig iron with air. An attempt to use a larger vessel nearly ended in a tragic accident. The vessel, or the converter, a little more than one metre tall, was made of sheet iron and lined with firebrick. As Bessemer would recall later, when the question arose as to the best shape and dimensions for the converter, he had very little to go by. The only thing he knew was that slag would be formed and ejected from all holes during the operation. He thought his vessel was large and tall enough, so nothing would fly out of it except hot gases and a few sparks.

However the things took a different course. Hardly ten minutes had passed after the blow was turned on when a jet of sparks emerged from the hole in the lid, growing stronger and stronger with every instant until it turned into a huge shaft of flame. Then loud popping sounds could be heard, and molten metal and slag went high into the air. The converter looked very much like a volcano during an eruption.

There was no way of approaching the 'volcano' and turning off the blow, and Bessemer found himself in the position of a helpless observer: a fire or even an explosion could happen any instant. Fortunately, nothing of the kind happened after all: a few minutes later the 'eruption' ceased. The metal tapped from the 'extinct volcano' was malleable iron.

The excited inventor ventured to repeat his experiment at once, having taken, as he thought, adequate measures to contain the fiery fountainhead: he suspended the round cast-iron lid he used to cover the coal pit by a chain above the hole in the converter. When, however, the blow was turned on and a new eruption began, the lid soon grew white-hot and melted. A few minutes later the only thing left to remind of the lid was a short piece of the chain that had once held it.

When in the summer of the same year Bessemer came to Cheltenham to attend the annual congress of British industrialists where he was to read a report about his process to a serious gathering of mechanics and metallurgists, he happened to hear an iron works owner advising a colleague to attend the morning session where he would find something to laugh at—a crank had come from London to tell them how to make iron without fuel, ha-ha!

That's true—the new process had more than enough of sceptics and opponents. It is interesting to note that when Bessemer applied for a patent in Prussia, the Patent Office in Berlin turned him down for the reason that "nobody could possibly be restrained from blowing air through molten metal". A forcible argument, indeed!

That was how the new process of making steel fought its way into industry—a process destined to play a stupendous role in the progress of world metallurgy and to glorify the illustrious English inventor for ever. It took him several years to refine his process. A major advantage of the converter process was that it took very little time to reach completion, and this led to a high throughput: the converter could turn pig iron into steel in a matter of twenty to twenty-five minutes while a puddle furnace could do the same in many hours. In terms of quality, too, Bessemer steel was superior to puddled iron on many counts.

Worldwide recognition came to Bessemer at the 1862 World Exhibition in London where a wide range of products made of Bessemer steel were shown. But even then not all manufacturers ventured to use the metal produced by so unorthodox a process. When, for example, Bessemer proposed to use steel rails instead of the usual wrought-iron ones the Chief Engineer of the London North Western Railway was extremely categorical in his response: he said Mr. Bessemer must be joking—the authorities would certainly send him to goal for manslaughter.

Nevertheless an excellent engineer himself, he took a risk. He asked Bessemer to send him ten tons of the material so that he could 'torture' it to his heart's content. And he did torture the test rails made of Bessemer steel. When he had become sure there wasn't any risk of being sent to gaol for manslaughter, he went to install new rails capable of standing up to the most severe tests.

The 1867 World Exhibition in Paris came as another proof that the Bessemer process was undoubtedly a practical success—that much was borne out by the gold medal it was awarded. While the puddling process had been slow in taking root at Russian iron works, the Bessemer steel produced in the Urals was shown already in Paris.

The correspondent of a Russian newspaper wrote in his report from the Paris Exhibition: "There is hardly a single country in the world, even with an insignificant iron and steel industry, where the Bessemer process isn't being used developed to some degree. Considering that the process is rather new, one cannot but agree that this invention is truly unprecedented in terms of the results for the industry which is now turning out up to 320 thousand tons of the valuable metal a year, and for the inventor who is collecting up to two million roubles in royalties every year".

If we recall that the inventor was far away from 'big-time' metallurgy just at the end of 1854 and that he took out a patent for the process that brought about a revolution in steel making in early 1856, we have every reason to apply to Bessemer the words once used by Julius Caesar: 'Veni, Vidi, Vici!'. In 1871 Bessemer was elected President of the newly organized British Institute of Iron and Steel, and in 1879 he became a Fellow of the London Royal Society.

To sum up, Bessemer had built what he had wanted—a good name and wealth. But the old age was closing in on him. With years the inventor lost interest in steel making and took to unorthodox projects—he could afford them now that he had a plenty of money and could let his fantasies carry him away. Since he had suffered from sea-sickness from his childhood, he thought of building a ship with cabins that wouldn't either pitch or roll. For this purpose he devised an elaborate system of supports, suspensions and hydraulic devices. The venture that had taken away six years ended in a complete failure and Bessemer suffered a sizeable loss. He was as unfortunate in an attempt to build a telescope of a size unheard of at the time. Anyhow, steel-making problems didn't interest him any more, but problems did crop up, and not small ones.

The point is that, apart from its unquestionable merits, the Bessemer converter had demerits as well. Above all, it couldn't handle just any grade of pig iron. If the pig iron had been made from an ore high in phosphorus (and many countries only had just such ores!), the phosphorus would pass into the pig iron and wouldn't leave it during the Bessemer process. The steel thus made was brittle and couldn't be practically used. Also the Bessemer converter could only make ordinary steel (that is, the metal good for ordinary uses), but nobody could make in it a steel for critical applications even from the best grades of pig iron.

Last but not least, the Bessemer converter could only take in molten pig iron, and it was beyond its capabilities to turn to steel the iron scrap that had accumulated in huge quantities in the past centuries.

That meant only one thing—a new quest for improvements.

Heat Goes Back to the Furnace

On the Way to the Stack — New Prospects — Is Everything Just? — A Pair of Earrings for Every Sister — The Gates Are Open — Away from the Factory's Din — Better Late than Never — The Steel Tombstone

Bessemer's fame was approaching its zenith when a new process, later called the open-hearth process, was invented in France for steel making, which was to crowd the Bessemer process into the background several decades later. Its inventor was Pierre Martin, a French metallurgist.

Several years before him, in 1856, that is, when Bessemer took out his main patent, the brothers Wilhelm and Friedrich Siemens*, German engineers, proposed an unusual way to heat a melting furnace—by utilizing the heat of combustion products. (There is an interesting detail: Wilhelm Siemens moved to England and lived in the same London street as Bessemer.)

The regenerative principle, as it was called, consisted in the following. Before they reached the stack, the hot gases leaving the furnace were passed through a brick checkerwork from one side, and gave up some of their heat to the bricks. After a short time the gas flow was shut off at that end, and air was introduced through the heated checkerwork from the opposite end and absorbed some of the heat stored in the bricks. The hot air then entered the furnace to sustain combustion and produced a higher temperature that could be obtained without preheating.

We have learned already that a similar idea was used by Cowper in 1875 in his hot blast stoves for blast furnaces. Soon the regenerative furnace came to be used in glass making, but the Siemens brothers' attempt to adapt their furnace to steel making remained barren although, as would seem, the high temperature thus obtained couldn't but hold special promise to metallurgists.

Strange as it may seem, it was the high temperature that impeded the adoption of regenerative furnaces by steel makers. At first, the charge was put in a crucible, and the crucible was loaded in a furnace, but both would then melt—the charge and the crucible. In some trials, even the furnace walls melted and once the furnace arch caved in. Still, the idea was extremely attractive and, of course, the metal-makers wouldn't renounce their hope to tame the process.

It fell to Pierre Martin to score a major success in 1864. Back in 1822 his father Emil Martin had come into the possession of an iron works at Fourchambot. After a year's instruction at the Mining School in Paris, Pierre, then twenty years old, took up a job at his father's works. In 1854, Emil Martin founded a new works at Civray not far from Angoulême and appointed his son its director. It was at this works that the open-hearth process was born.

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* Sometimes their names are written as Wlliam and Frederick.— *Translator's note.*

The Martin father and son had begun their attempts to produce cast steel by melting a charge of pig iron and scrap on the bottom of a reverberatory furnace well before the Siemens brothers made their invention. However, nothing had come out of their attempts because the temperature in the melting space wasn't high enough. The regenerative principle changed everything radically.

From the drawings produced by Wilhelm Siemens, Pierre Martin built a regenerative steel furnace, using for its walls and arch English silica firebrick capable of standing up to high temperatures. That was a happy choice of materials—the cast steel made in the furnace was of an acceptable quality. In the same year Martin took out a patent for the new process in France and England, then several more patents covering the various aspects of the process in the succeeding years.

Is it just to take Martin as the inventor of the new process? Is it right to ignore the valuable contribution made by the Siemens brothers, especially Wilhelm who did more than Friedrich to adapt heat regeneration to steel making? Incidentally, the Germans call it the Siemens-Martin process even now.

Martin's services are unquestionable. Owing to many years' metallurgical experience, he knew all the niceties of steel making far better than Siemens did. Indeed, he carried the idea an important step forward by proposing to use furnace gases in order to heat not only air, as was envisaged in Friedrich Siemens' original plan, but also gasified fuel—a thing which had a wholesome effect on the run of the process. Nor should we discount the happy choice of refractories: apart from the silica firebrick that Martin used for the walls and arch of the furnace, he fell upon the idea of using local silica sand which was sintered into the bottom of the furnace.

On the other hand, Martin stressed more than once that he owed a good deal of his success to the heat regeneration principle thus paying their due to the Siemens brothers. In fact, he signed a number of contracts with Wilhelm under which the latter had a share in the royalties and was granted the privilege of building regenerative steel furnaces and serving as an official consultant in matters related to the organization of the process.

The jury of the World Exhibition held in Paris in 1867 did as the Russian saying goes: they gave a pair of earrings to each sister: Pierre Martin was awarded the Great Gold Medal for his steel and Wilhelm Siemens, a Grand Prix for his regenerative furnace.

Lasting, as it did, several hours, the open-hearth process was a slower one than Bessemer's, but it produced steel of a higher quality. Also, and perhaps more importantly, it offered an opportunity to re-melt steel scrap, including the waste metal from the Bessemer process, of which quite a lot had accumulated at iron and steel works. The Bessemer converter remained unquestionably a better performer in terms of rate of production. Thus, the two steel making processes complemented each other, as it were, and weren't rivals.

The open-hearth furnace was indiscriminate towards the charge materials: it submissively took in any pig iron, any scrap, and any iron ore. It was only necessary to make a correct choice of the process variables so that they suited the relative amounts of the charge components. While the Bessemer process didn't practically lend itself to control, its open-hearth counterpart was easy enough to monitor and to make adjustments—if and when necessary. Also, the open-hearth furnace could produce a wide gamut of steels, which the Bessemer converter wasn't able to do.

The iron and steel works in all industrial countries welcomed the open-hearth furnace. Steelmakers in Russia, too, took a deep and logical interest in the new process. Russia's first open-hearth furnace was built by A.A. Iznoskov, a young engineer, in 1870. The 2.5-ton open-hearth furnace he had built at the Sormovo Iron and Steel Works in the city of Nizhny Novgorod was technically superior to the early furnaces built by Martin. It was soon followed by a 1.5-ton furnace at the Votkinsk Works and by a 5-ton furnace, a very large unit for its day, at the Obuhov Works in St. Petersburg. By the 1890s Russia had over a hundred open-hearth furnaces in operation.

While the open-hearth process was successfully winning the recognition of metallurgists the world over, its inventor who had retired from factory matters in 1883 was living an inconspicuous life in the small family estate at Fourchambot. In contrast to the shrewed and assertive Bessemer, Martin had failed to cash in on his invention. Indeed, he even lost what he had earned very soon. It was no mere chance, though. For Bessemer, a professional inventor turned metallurgist by the will of fate, knew everything related to patents inside out. Martin was a professional metallurgist with a poor knowledge of patent laws. As he sailed in the stormy patent sea, he often ran into snags and ran aground. And since it likes to live next to wealth fame didn't treat him well too often. Gradually, everybody forgot him.

In the early 20th century, however, the open-hearth process outperformed the Bessemer process in the scale of production, and Martin again became everybody's talk. The French industrialists who had netted fortunes on open-hearth steel decided to erect a monument to Martin, thus perpetuating the contribution their unjustly forgotten countryman had made to world metallurgy. They made inquiries about the dates of his life so as to time the event to some anniversary. How great their surprise was when they learned that Pierre Martin was still alive but was living in poverty.

In 1909, the association of French metal-makers held a festive meeting in Martin's honour. The 85-year-old hero of the festivities was invited to sit on the podium, next to the owners of big iron and steel works, leading scientists, and top executives from major iron and steel companies. Many good words were spoken about him, and many greetings came from other countries. Martin was awarded a memorial gold medal on behalf of the world metallurgical community, and the French government conferred upon him the officer's cross of the Legion of Honour. Well, better late than never. And the two hundred thousand francs collected for the poor great old man by international subscription came in good time, indeed.

But there was more to come in recognition of Martin's services. In 1915, the British Institute of Iron and Steel awarded him the Bessemer gold medal usually given to mark outstanding discoveries and inventions in the field of metallurgy.

Fame seemed to have realized its guilt and was in a hurry to confer upon the remarkable French inventor ever more honours. But his life was drawing to an end: on May 25, 1915 Pierre Martin died at the age of ninety. A massive slab of excellent open-hearth steel was put on his grave.

The New 'Attire' for the Converter

Chance Remains True to Itself — In the Police Court — The Beam of Light in the Dark Basement — Where Is the Rub? — The Table of Ranks — Don't Be in a Hurry — On the Right Course — Events in Paris — Aston Becomes a Mecca — "He's Won the Battle Splendidly" — The Strong Competitor

The open-hearth process brought with it an opportunity to use the iron scrap that had accumulated over centuries. But the problem of using pig iron high in phosphorus in the Bessemer converter remained as unresolved as ever.

Attempts to crack this hard nut were made by steel-makers in England, France and Germany. The Germans were especially interested in such a process because when God created the world and shared out minerals, what fell to the lot of the lands that later made up the German state were iron ores high in phosphorus. A sad joke was current among German iron-makers, saying that their iron ores were so rich in phosphorus that they were all but glowing in the dark. German industrialists were forced to buy iron ore low in phosphorus from their foreign competitors, a fact which obviously didn't help metallurgy in the country.

Chance, as you may have noticed, had since long been playing into the hands of English metallurgists. Recall Huntsman and Darby, the Cranege brothers and Cort, Cowper and Bessemer. Now chance chose to turn its eyes on one more Englishman.

He was Sidney Gilchrist Thomas born in 1850, or six years before the Bessemer converter first appeared on the scene. In just few years their fates were to be interwoven closely, and Thomas was destined to expand the capabilities of the converter, and it was to bring world-wide fame to Thomas.

As a youth, Sidney took interest in the natural sciences. But his dream to be a physician never came true: when he was seventeen his father died, and the young man had to support his mother and sisters. For lack of any other opportunity he took up the job of a clerk at the London police court. But he never gave up his thoughts of education.

Soon he could be seen spending his evenings at the Royal Mining School, listening to lectures read by scientists well known in England. One of them was Professor John Percy mentioned earlier in this book. Educated as a physician, Percy took up biology and zoology but soon realized his true calling was metallurgy. His colourful personality had great impact on Thomas: from Percy's lectures he learned that everything taking place in any smelting furnace was based on chemical laws.

It was chemical insight into steel making that probably played the leading part in the success scored by Thomas when he set about to tackle the metallurgical problem so urgent at the time — removal of phosphorus from the metal in the course of the converter process.

The first refuge for Thomas in his quest was a cramped basement in a London street. There, assisted by his cousin, Percy Gilchrist, a chemist at a works in South Wales, he set up a simple laboratory and started his experiments, using a miniature converter which could hold a mere six pounds (a bit less than two and a half kilograms) of pig iron. He knew that phosphorus could be removed from the molten metal only if there was a suitable chemical 'environment' in the converter: the phosphorus would agree to leave the metal only if there was a basic slag next to it (that is, a slag consisting of basic rather than acidic oxides) and this, in turn, required that the refractory lining of the converter should likewise be basic or else it would be eroded and fail. With all of these requirements satisfied, the naughty phosphorus would be oxidized as the pig iron was blown with air and would form with the components of the slag a union so strong as to be unresolvable. It seemed clear what to do, but, as it turned out, to do this was not at all easy. Where was the rub?

It was simple enough to 'build up' a basic slag, but nobody could find for a long time a suitable basic refractory material for the walls of the converter, a material that would be able to stand up to all the thermal and chemical consequences of the blow.

The lining used in the Bessemer converter and the open-hearth furnace was made of sand, or silica, which is a base. The material was good enough to bear the brunt of the smelting operation, but it obviously wasn't a match for phosphorus. There was a hope that the treacherous enemy of steel could possibly be overpowered with magnesite, limestone, or dolomite, each made up of basic oxides, but experiments made one after another left the problem unresolved. Either the lining wouldn't be staunch enough and would fail or, on the contrary, it would be too staunch and the phosphorus would stubbornly refuse to leave the metal.

That was how things stood when a firework of sparks was first seen in the twilight of the London basement: working alone or, sometimes, in company with his cousin, Thomas tried one charge of pig iron after another. The lining he used was a mixture of crushed limestone and water glass. Even the first results were encouraging. However, the small laboratory vessel which could be called a converter only by a stretch of imagination was one thing, and a commercial converter capable of holding tons of hot metal was quite another. The cousins were able to talk the owners of the works where Percy was employed into letting them carry out large-scale trials. The converter they were allowed to use was a relatively small thing—it could hold a mere 150 kilograms of charge, but it was a commercial converter, all the same.

Ignoring his poor health and severe cough (the hard years of work and study coupled with scanty food and a damp basement had spurred an early tuberculosis), Thomas wouldn't leave his converter literally for an instant. He made ten heats and was finally able to reduce the phosphorus content of the steel to just a few hundredths of one percent.

Why was it that dozens of other metallurgists had failed although they did the same and the success came only to him?

One cause was this. The impurities present in pig iron don't burn just at any time, when the pig iron is blown with air, but do so according to a kind of table of ranks which is based on the chemical properties of the elements and, above all, their affinity for oxygen. Nobody can violate this order. Of all the elements present in pig iron, the unquestionable right to burn first goes to silicon. It may then be followed by manganese and, in part, by iron itself. That's when the turn of carbon comes, and it throws itself in the flame's embrace at once.

Gradually, the supply of carbon is running short, and the converter fire begins to subside. It was at that instant that most steel makers would turn off the blow both in the Bessemer process and in many trials involving pig iron high in phosphorus. They perhaps reasoned like this: since the flame was subsiding, it was an indication that all that could burn had already burned, and there was no sense in blowing the metal with air any longer as this might cause the iron itself to burn. This kind of reasoning was valid for the Bessemer process, but those who wished their steel to get rid of its phosphorus oughtn't to be in a hurry.

That's where the rub was. When the impatient steel makers turned off the blow, it wash't yet time for the phosphorus to become oxidized. With the blow turned off, however, it remained intact. Thomas thought differently and went on with the blow. Now the turn came for the phosphorus to add 'wood' to the fire. It was found that, on burning, phosphorus gave up a lot of heat (it reacts exothermally, as chemists would say), being second in this respect solely to silicon.

True, it was hardly likely that Thomas had a clear idea about all the fine things that take place in the process even after his first successful trials at the works, but he was on the right course. In late 1877 Thomas took out a patent for a modification of his process related to removal of phosphorus, and sold it at once because he needed money with which to carry on his experiments. As he wrote to his sister, he had conceded the right to use his patent to a man he knew for a very small fee. But he pointed out that he had scored a success at last and was eager to carry on his work. He had an idea but it was hard to make it work, he added. He asked her not to be worried about his health as he was coughing less.

But that wasn't true. His cough grew more severe with every day. Nevertheless, he went on with his trials, looking for the best material for the converter lining. Gradually, Thomas formed a firm belief that his purpose could best of all be served by dead-burnt dolomite. The dolomite walls could stand up to attack by the lime which was needed to built up a basic slag eagerly absorbing the phosphorus as it was leaving the metal.

Much as a photograph turns ever more distinct as it is developed, so the picture of the process grew ever more clear to Thomas with every heat. Now he saw that the ingredients of the success were the walls of dolomite, the slag of lime, and the blow maintained to the victorious end. Thomas took out a patent, and the year 1878 has come down into the history of steel making as the year of the birth of the Thomas-Gilchrist process*.

Few people knew about Thomas's experiments. It was small wonder, therefore, that Professor Bell, a Fellow of the Royal Society, speaking at a meeting that the British Institute of Iron and Steel held at the Paris World Exhibition just a few days after Thomas had taken out his patent, declared bluntly that the problem of phosphorus removal (more known technically as dephosphorization) hadn't yet been resolved. Thomas who had also come to Paris made an attempt to raise an objection during the discussion, but the ill-looking, skinny man in shabby clothes could hardly evoke sympathy with the prosperous public. Indeed, his claim to confront the famous Bell himself made angry some of them and set laughing others, but nobody approved of his action. In short, Thomas wasn't allowed to take the floor.

Among those present at the meeting which literally put a gag in Thomas's mouth was the venerable Bessemer. Fate sometimes makes strange turns and moves: could the inventor of the converter, who had failed to conquer phosphorus, think at the time that a few years later he would award the gold medal bearing his own name to Thomas, then already famous as a man who had delivered the converter from a grave shortcoming and supplied steel makers with a reliable remedy for phosphorus disease?

But recognition was yet to come to Thomas, and now he was engrossed in trials on a large converter capable of holding several tons of hot metal. One heat followed another and still another. Thomas carefully analysed his findings, made whatever adjustments he thought were necessary, and applied finishing touches to his process. There could be no doubt: his process could resolve the problem of phosphorus on a commercial scale.

Thomas made another attempt to report his findings to the luminaries of metallurgy. In September 1878 he went again to Paris where the World Exhibition was still under way and where the British Institute of Iron and Steel was to hold its autumn session. Quite a number of papers were read there, and lively discussions took place in the lobby, but nobody wanted to listen to Thomas's report on one of the most urgent problems of metallurgy at the time: for 'lack of time' his report was removed from the agenda and shelved until the next session of the Institute.

Well, let it be the next session. Nature had been stingy in giving Thomas poor health, but it had given him a lot of brains, patience and perseverence. Nor did Thomas waste his time on trifles. The manager of the works at Aston where big Bessemer converters had recently been built took justified interest in the young inventor or, rather, in his process which held promise of sizeable benefits. Thomas was offered a new opportunity to bring his process to perfection on a commercial scale. In the spring of 1879 Thomas took out a patent for an improved embodiment of his process. Now that he had carried out his last trials at a well-known works and they had been given wide publicity, his report at a session of the British Iron and Steel Institute was received with due attention. The conference hall was capacity full of top executives from many metal-making companies all over Europe.

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* Ironically, it is more widely known as the basic Bessemer process.

Thomas's public appearance ended in triumph. Soon prominent industrialists were offered an opportunity to see his invention in action: the management of the works at Aston invited them to watch the converters in operation. For some time, Aston looked like a Mecca for metallurgists from many countries. Several months later two works in Germany and Luxemburg tapped the first heats and rolled rails from the Thomas steel produced on the same day. As tests showed, the rails could satisfy the most exacting customers.

Obscurity and poverty now belonged to the past, although, the inventor had to beat off quite a number of attacks by his competitors who questioned his priority, the novelty of the invention and, therefore, his right to receive royalties for the reason that some details of the process had been disclosed in the technical literature and had even been adopted in industrial practice. But, much as one cannot turn a broken vase into a whole one by simply collecting and putting together all the shards—it can only be made anew, so the Thomas process, covering all the aspects of phosphorus removal, substantially differed from the earlier specific ideas and proposals. Yet, the inventor was summoned to give his explanations to the Royal Patent Council. Fortunately, his supporters included not only the truth itself, but also the industrialists who had bought his patent and prospered through its use. All claims were swept aside, and the companies wishing to adopt the new process—and there were quite a few of them—had to buy licences from Thomas.

The Thomas process was practised on an especially large scale in Germany—for the reasons already known to the reader. In a way, Thomas had opened a channel through which millions of tons of cheap high-phosphorus ore so far lying useless in the womb of the German lands came down in a powerful stream to iron and steel works, tremendously boosting steel manufacture in Germany. A year later, all iron and steel works in Germany were using the new process.

Thomas had become the talk of the entire world. He was given an enthusiastic reception in America where the captains of industry hailed him as the saviour of steel from phosphorus disease.

But, unfortunately, he couldn't get rid of his own ailment. Nothing came out of his voyages for a cure to Australia and Africa. After a short but illustrious life, Thomas died in Paris in 1885. The inscription on his tombstone reads that he won the battle splendidly.

By the end of the 19th century the Thomas converter had left far behind the open-hearth furnace in terms of the scale of production and remained second only to its elder 'brother', the Bessemer converter. Since high-phosphorus iron ores carried a lower price, Thomas steel was cheaper to make than Bessemer or open-hearth steel. In terms of quality, however, open-hearth steel was better than that produced by the converter process because it contained a high percentage of nitrogen left over from blowing the metal with air. Phosphorus, too, sometimes let itself be felt. Because of this Thomas steel had many opponents, especially in the inventor's own country where the problem of phosphorus wasn't so acute as in, say, Germany. Indeed, Lloyd's, the society of underwriters in London, even raised the rates of insurance for the ships built from Thomas steel.

In the early 20th century, the open-hearth process came to the top of the list of steel-making processes, and the Thomas process was falling into the background. Doesn't it seem that Thomas's contemporaries were too much in a hurry when they hailed his services? The answer is 'No'. In the opinion of John Bernal, a prominent British scientist and public figure, the authour of many books on the history of technology and the role of science in society, Thomas's invention was a scientific one from start to end. He also notes that Thomas's work set the standard for scientific research in manufacturing for the next century. The significance of Thomas's invention for metallurgy goes beyond the limits of the converter processes: the basic lining he proposed for the converter came to be used in the open-hearth furnace as well and made it more versatile and flexible. Quite logically, in the years that followed the inventor's death nearly all open-hearth furnaces switched to the basic process, leaving the acid process for a limited range of furnaces.

The turn of the century saw both a stiff competition between the open-hearth and converter processes, and the advent of another piece of steel-making plant which offered metallurgist an opportunity to produce steel of an extremely high quality. This piece of plant was the electric arc furnace. The flame that had been the sole owner of all rights in the smelting of metals faced a strong competitor—electric current.

Lightnings in the Furnace

Going Off the Stage — A Jinnee in Captivity — The Century-Long Road — Just in Case — The Barrier is Lifted — At the Turn of the Century — What are Spices for? — During World War I

Time hasn't been so favourable to the inventors of the electric steel-making process as it was to Bessemer, Martin or Thomas whose names given to processes and steels are known today to any metallurgist and, indeed, to any one interested in the history of technology. The electric steel-making process has remained nameless although it has been more fortunate than its predecessors; since it was first proposed, it hasn't practically changed: its position is as strong as ever and it has bright prospects ahead. In contrast, the Bessemer and Thomas processes have played their roles and gone off the metallurgical stage, and the open-hearth process, with its haydays already far in the past is about to follow their suit.

The reason why the electric steel-making process has remained nameless lies, in all probability, in the fact that it has been invented, developed, and put to use by many scientists, designers and technologists. Among those who stood at the cradle of electric steelmaking was V.V. Petrov, Professor of Physics at the St. Petersburg Academy of Medicine and Surgery (later elected a member of the St. Petersburg Academy of Sciences).

The closing year of the 18th century brought with itan important discovery in physics. The discovery was made by Alessandro Volta, an Italian physicist: he built the ever first source of electricity—the Volta pile, or the galvanic cell, which set physicists all over the world looking for the practical uses to which the pile could be put. In 1802, Petrov carried out a series of experiments in which he used 'a huge battery consisting of 4200 copper and zinc discs'.

A year later he published his findings in a book, "A Report on Galvani-Volta Experiments". In one of its chapters, entitled "On Melting and Burning of Metals and Many Other Combustible Substances, and on the Conversion of Some Metallic Oxides to Metals through the Agency of the Galvani-Volta Fluid" (that is, electric current), he wrote: "If we place on a glass plate or a bench with glass legs two or three pieces of charcoal capable of producing light when acted upon by the Galvani-Volta fluid and if, then, we move the charcoal pieces closer together with the aid of insulated metal guides connected to the poles of a large battery, we will see between them a very bright, white light or flame causing the said carbons to go ablaze sooner or later and capable of illuminating a dark room brightly". It's a sure bet that the reader has guessed what's it all about: Petrov was the first in the world to produce an electric arc (or the Volta arc, as it was called at the time).

The scientist felt that electricity wasn't unlike a mighty, but submissive jinnee held in captivity in a corked bottle. It remained only to set it free and to guide its ebullient energy into a proper channel. But how could that be done? In his search for an answer, Petrov re-arranged his experiments in various patterns. He replaced one of the carbon electrodes with a metal one and kept close watch on how a particular metal behaved under the action of the electric arc. He came upon an intriguing finding. As he wrote, "a flame of varying brightness" appeared between the electrodes, and this flame "caused the metals to melt, sometimes at once".

As an outcome of his experiments, the scientist found that the electric arc offered a possibility to produce metals from their compounds, that is, to extract them from suitable ores. As he wrote in the same chapter, "Finally, using the flame accompanying the flow of the Galvani-Volta fluid from a huge battery, I tried to convert the red oxides of lead and mercury and also the grayish oxide of tin to metallic forms. When the said oxides were mixed with crushed charcoal, tallow and expressed oils, and these combustible substances were burned, the oxides sometimes took on a true metallic appearance".

That's how Petrov fell upon the idea of using an electric arc for metal melting and metal extraction from ores. But his idea was to travel a century-long road from inception to practical use in steel making.

In 1853, or fifty years after Petrov had made public his findings, a patent was granted in France for an electric furnace intended to make steel. Curiously, the patent envisaged, in addition to a large battery, the usual firebox—a century-tested and reliable source of heat.

Another quarter of a century had passed before Wilhelm (or William) Siemens designed an electric furnace in which he was able—for the first time ever—to extract iron from ore. His furnace was, however, far from perfection, and the iron thus produced carried so much of objectionable impurities that its practical use was out of the question. Nevertheless, his work drew the attention of the technical community all over the world. As a correspondent of the *Electricity Journal* wrote in 1880, "Does the Volta arc produce enough heat to melt large bulks of metal? This question has of late been answered by Siemens' interesting work. During our recent visit to London we were eye-witnesses of how over a pound of steel was melted in less than five minutes by the heat generated solely by electric current. The electric hearth will undoubtedly hold a prominent place in chemical work, in the melting of precious or refractory metals and in some other cases where economic considerations are of minor importance, and its role in the future will only grow in importance".

In 1891, N.G. Slavianov, famed for his invention of electric arc welding, was first in the world to use small crucible furnaces fitted with electrodes to melt steel and some other metals in Perm where he was Chief of the Gun Works.

Another man who did much in this field was Henri Moissan, a French chemist and metallurgist. He spent several years building a laboratory electric metal-melting furnace which was presented to the Academy of Science in Paris in 1892. An unquestionable merit of his furnace was that it could raise the temperature to as high as 4000°C. Later, in 1906, Moissan was awarded the Nobel Prize for his studies and a method for the extraction of fluorine and for a scientific application of the electric furnace known by his name.

All of this early effort, however, covered a very limited ground and couldn't offer a complete solution to the problem of large-scale steel making by means of the electric arc. The industrial use of electricity was to a great extent hampered by its high cost. This barrier was finally lifted towards the end of the 19th century: the early hydroelectric power stations built one after another in Switzerland, Sweden, Germany and the United States went into commercial operation. The sizeable fall in the cost of electricity spurred research and development work in the field of electric metallurgy. Before long Paul Louis Héroult in France and Ernesto Stassano in Italy built, almost at the same time, electric arc furnaces of a fairly good design. The Héroult furnace in Savoie produced the first heat of steel in December 1900 when the 19th century was counting its last days and preparing to resign its commission to the 20th century. That was how, at the turn of the century, electric steel made its first appearance.

Because the conditions inside the electric furnace were especially favourable (a temperature of as high as 5000°C in the arc zone and a reducing atmosphere), metallurgists were now able not only to free the metal from objectionable impurities, but also to make alloy steels, that is, steels containing a wide range of quality-improving additions. What are these additions like?

Much as a sophisticated cook adds spices to prepare a savoury meal, so a steel maker uses alloying additions in order to turn out a grade of steel which has valuable properties of his choice. Every spice serves a purpose of its own: some improve flavour, others add an aroma, and still others make it appetizing. It is a job of work to name everything that spices can do, but it is far more difficult to list all the remarkable properties that a steel gains when some chromium, nickel, titanium, tungsten, molybdenum, vanadium, zirconium or other element is added to it. Most of these elements melt at a higher temperature than does iron, therefore it is the electric furnace alone that can provide a suitable 'climate' for these refractory ingredients to be added to the metal.

Metallurgists and mechanical engineers were quick in taking to electric steel. Early in the 20th century electric steel furnaces were installed in Germany, Sweden, Britain, the United States and some other countries. In 1910, two such furnaces brought from abroad went into operation in Russia, one at the Obuhov Works in St. Petersburg and the other at the Iron and Steel Works in Makeyevka.

The demand for electric steel truly sky-rocketed during World War I when large quantities of high-quality steel were needed to make artillery pieces, armour and similar products. Towards the end of the war, electric steel output was many times the pre-war figure. Although its share in world steel output remained modest, metallurgists were aware of the bright promise held by the electric furnace in which the metal is melted by man-made lightnings.

The Points That Dotted the I's

How Otello's Sword Was Hardened — The Ram, the Goat, or the Red-Haired Boy? — At the Mint — Changes in Life — Where to Begin? — The Flash That Lasted a Wink — Two Points More — The King-Sized Crystal — Herostrate's Laurels — 'I Take It My Duty...' — The Unfulfilled Mission

Over millenia, since the early smelting pits to our time, metallurgy has been in a never-ending search for ever better ways and means of making and working metals. Until about the mid-19th century, it was, in effect, a blind search: 'experience, an offspring of grave errors' was the only and not always a reliable tool of learning that the metallurgists had in their possession in the past, forced to proceed by trial and error. There was an acute need for a 'compass' by which metal-makers could take their bearings on their journey to new discoveries and in their inquiry into the mystery of the flame-sustained processes. Such a 'compass' could and must be supplied by the science of metals.

Even in ancient times metal-makers knew that the properties of a metal depended both on its nature and on the way it was treated. Some fifteen hundred years before Christ an interesting observation was made: when an article made of a carburized iron was raised to a red heat and then cooled rapidly in water or some other liquid, it would become very hard and strong. This is hardening—an important form of heat treatment for steel even today. Nobody could explain at the time why raising to a red heat followed by rapid cooling, or quenching, produced a harder and stronger metal, but there were quite a number of prescriptions how to go about it: almost every master had a secret of his own. This is what has been found in the chronicles of a temple in Asia Minor, dating back to the 9th century B.C.: "Heat the dagger until it shines like the sun rising in the desert, then quench it by thrusting it into the body of a muscular slave until it takes on the colour of royal purple. As it passes on to the dagger, the slave's strength makes the metal hard".

A different 'know-how' was used by Damascus armourers who made their famous steel blades as early as the end of the first millenium before Christ. As the legend goes, they hardened their blades in a mountain gorge where strong winds blew. It was believed that the winds passed on their strength to the blades. Smiths in ancient Georgia hardened their steel articles in a similar way.

To believe Shakespeare, Otello's sword was hardened in a stream cold as ice.

However, many masters believed that such simple quenching media as water and the wind were obviously not enough to assure high qualities, and proposed their own approaches, more elaborate but, as they thought, more efficient. One was described by Theophilus, a medieval German writer: "Take a three-year-old ram, fatten it tightly, and leave it unfed for three days. On the fourth day, feed it with fern. After two days of such feeding, place the ram for the night in a cask with holes made in its bottom. Place a vessel under the cask to collect the ram's urine. Remove the urine thus collected in a sufficient quantity over two or three nights, and quench the tool in said urine".

Either from lack of knowledge or from lack of a ram, some masters used a goat; still others thought it was a good idea to do quenching in the urine of a boy, preferably a red-haired one.

Strange as it might sound, but there was some reason in these prescriptions: urine and other salt solutions absorb the heat from the white-hot metal faster than does the coldest water. Having noticed, obviously by chance, this trait of salt-bearing liquids, medieval metallurgists indulged in variations on this theme and were sometimes highly successful.

In the 18th century, iron-makers at the Ural Works, Russia, devised a hardening technique in which the quenching medium was a mixture of cattle horn and salt. The axes, knives and sabres thus hardened remained sharp for a long time and didn't rust.

What was the secret of this technology? It didn't lie so much in the manner of quenching as in the prolonged soaking of the steel made in bloomeries. Steel articles were packed along with cattle horn and salt in boxes and held in a furnace without access of air at a high temperature. Thus treated, the steel was then quenched in the usual way.

Nobody knew at the time what happened to the iron held in company with cattle horn in the soaking boxes. And what happened was nothing but nitriding, or surface impregnation with nitrogen. It is interesting to note that even today steel articles are nitrided by immersing them for several hours in a melt of potassium ferrocyanide obtained from horns and hoofs as they are heated in a mixture of iron filings and potash.

While using various prescriptions in their practice, metal-makers have always been trying to explain them and to get insight into the events. As early as several centuries ago, alchemists (who were mainly responsible for metal making) tried to lay a scientific foundation for metallurgy. A 'valuable contribution' to the science of metals was made by Magnus, a 13th-century alchemist, who is credited with the following theoretical 'discovery': "Steel is nothing but iron, only much cleaner because the watery part of the iron is removed by distillation; also, steel is harder and denser than iron owing to the action of fire; it becomes the stronger, the oftener it is heated. Steel becomes whiter due to the separation of earthy impurities, and when it becomes too strong, it cracks and bursts to pieces under a hammer because of excessive dryness".

In the mid-19th century, such unorthodox 'scientific' views would have sounded strange, to say the least, but the essence of the events taking place in the metal, notably steel, remained a mystery. This is what the author of a book published in Germany in about those years wrote:

"The most valuable property of steel, owing to which it is indispensable in the manufacture of cutting tools, is the fact that it can acquire softness and extreme hardness through the agency of changes in temperature alone. It is known that when it is heated and then allowed to cool slowly, steel becomes perfectly soft and can be worked as easily as the softest iron. If, on the other hand, steel is heated and rapidly cooled by, say, immersing it in cold water, the metal acquires so high a hardness that even the best file can't work it. However, so hard a steel can, by heating it slightly (that is, by tempering) be made to lose its brittleness and to acquire the desired degree of hardness. When heated to less than a white heat, steel will not harden even when quenched in cold water, but, on the contrary, becomes surprisingly soft. The technicians use all of these findings to achieve various goals and techniques of quenching are chosen to suit them. The English, for example, kept quenching in molten lead or tin a secret for a long time. What happens in the steel as it softens and is heated has not yet been explained theoretically".

The above passage comes from a German book, "The Exploits of the Human Mind" which was translated into the Russian and saw the light of day in St. Petersburg in 1870. About the same time the human mind had performed another exploit: in 1868, Dmitry K. Chernov, an outstanding Russian scientist, unravelled the mystery of steel, determined the temperature points at which steel undergoes structural changes on heating and cooling, and described in rigorous scientific terms "what happens in the steel as it softens and is heated".

After he had graduated with honours from the St. Petersburg Practical Institute of Technology, Chernov was sent to work in the mechanical shop of the Imperial Mint where his father had been a physician's assistant at the local hospital for many years. The young technologist, or a 'conductor, first class', as he was officially named in his papers, noticed an intriguing thing: some dies that made coins would last tens of hundreds of operations, while others made of the same hardened steel would develop cracks in just a few strokes. Why?

Chernov was unable to answer the question at the time. Also, Ilya P. Chaikovsky (father of the famous composer), who was Director of the Institute of Technology, and did much to promote mining and metal-making in Russia, obtained from the Finance Ministry which was in charge of the Mint the permission to transfer Chernov back to the Institute "to compile a systematic catalogue of the machines, tools, and other devices held in the Technical Museum, and also to teach mechanical drawing". This change in his life made Chernov happy: he had before him an excellent opportunity to expand his knowledge—a thing he was after all his life. True, he was less happy about the prospects of teaching mechanical drawing, but some time later he was appointed assistant curator of the Museum and librarian.

The Institute's large library had a wealth of literature on metallurgy and mining, and its recent alumnus found an excellent opportunity to expand his education, carefully reading tens of books and journals in Russian, German, and French. As a free-attending student, Chernov could often be seen at lectures in the Department of Physics and Mathematics of the St. Petersburg University. He spent a good deal of his free time in the Institute's chemical laboratory as well, acquiring skills in the analysis of metals.

Several years passed. In the meantime, the young scientist had accumulated a substantial store of theoretical knowledge, but he had a flair for practical activity, and so in 1866 he willingly accepted the invitation to take up a job at the recently built Obuhov Works. As a member of an expert group, he was to diagnose the 'illness' that had spread in the manufacture of cast steel guns. For some reasons nobody knew the Works' products were amazingly inconsistent in properties: among excellent guns capable of firing thousands of rounds, there were units that went to pieces at the first shot on the proving ground.

That was the first assignment the young man was to tackle at the Obuhov Works. It wasn't unlike the one he had handled when he was with the Mint. What was to be done first?

As Chernov would recall later, he was set on a correct course by his study into the structure of many guns—both those which had had a long service life behind them and those which had burst after a few shots. He spent many days and even nights at the Works, pains-takingly examining with a magnifying glass the metal where it had burst, viewing microsections in a microscope, and testing steel specimens in the chemical and mechanical laboratories. At last he was able to establish a well-defined relation: the stronger pieces of steel were those which had a fine-grained structure. And the best guns, too, were made of fine-grained steel, while the burst barrels showed a coarse-grained fracture. But the chemical analysis was the same in both cases. Therefore, it was necessary to find why it was that steel had a fine-grained structure in some cases and a coarse-grained structure in others, a fact which led to flaws in the metal and, sometimes, to deplorable consequences.

Chernov switched his attention to the smithery. It was there that the steel foundry sent its massive steel ingots and it was there that a powerful hammer turned them into billets. After hammering, the billets were quenched in water and passed on to the next shop to be machined into gun barrels.

But before the huge hammer of many tons in weight came down on a steel ingot, the latter was re-heated in a soaking pit to make it softer and more manageable. How much should the ingot be heated in the soaking pit before forging? Instruments to measure high temperatures were non-existent at the time (the thermoelectric pyrometer was invented by Le Chatelier, a French scientist, in 1885), and the smiths estimated the temperature by eye, from what are known as 'heat colours' and which range from an incipient red heat to a dazzling white heat, as the temperature of the metal is raised.

Chernov would stay at the soaking pit for hours on end, noting all changes in the colour of the hot metal. Before long his observing eye acquired the knack of telling the amount of heat an ingot had received more accurately than the most experienced masters could do. But couldn't it be that the crux of the matter was not in the heat the ingots received but in the loads they had to bear in the course of forging? There was a school of thought at the time which maintained that the fine-grained structure could only be obtained by heavy forging.

Chernov made simple but accurate tests which he described nearly a half-century later: "The tests ware carried out as follows. We took a bar of steel and cut out of it at different places several specimens for mechanical testing. Although in practice the metal is soaked before forging, we didn't do that so as to exclude the effect of temperature, and forged the specimens with a heavy hammer operating at a high rate to a different thickness within the various portions along the specimen. There was no difference in temperature between the ends. The structure was examined with a magnifying glass, and I noticed no difference in metal constitution at any section. Also, I found that the steel hadn't become denser—it had the same specific gravity at any point along the forged specimen. Then I did the same kind of forging at different temperatures. This produced a noticeable difference in structure, readily seen in a magnifying glass. From what I had seen, I concluded that the changes in structure should be ascribed to the effect of temperature and not to forging. I also found that this change in structure would take place not at just any temperature but at some particular point which was different from steel to steel. Now the task was to determine these points for all grades of steel".

"To find these points". Today, this can readily be done by any metallurgical student who has an array of instruments at his disposal, but over a century ago the task was one of hardly manageable difficulties. Time and again Chernov heated and forged steel specimens, cooled and tested the metal, while keeping a close watch on it at every stage of the experiments. One day, when an ingot was slowly cooling in the air, Chernov noticed an intriguing thing: at some instant the slowly darkening metal was suddenly lit up by an internal light. The flash lasted for not more than an instant, and the metal went on cooling off and darkening as if nothing had happened. Couldn't it be just the trick of his eyes tired of the permanent strain? Chernov made experiments one after another, and each time the steel seemed to signal him about something. But what was this 'something'?

Nothing could be learned about the mysterious flash from the old masters who had worked in the smithery for decades: they either didn't notice any flash at all or dismissed it as something unimportant. Nor did they have a chance to see it often: as a rule, the billets were rapidly cooled in water, and the metal had no opportunity to flash for at least an instant as it parted with its heat. Nor was there a single word about the event in the technical literature.

Chernov hypothesised that the flash occurred just as the cooling steel was passing through some point on the temperature scale, where some change took place in the metal. A new problem faced the investigator: he was to find what change it was. In an attempt to solve it, he compared two forgings: one which 'flashed' before quenching, and another which was dipped in water before the flash. The subsequent mechanical tests showed that the first forging didn't become any harder—it had refused 'to take the quench', while the second did become harder. On repeating the experiments many times, Chernov was convinced that there was some regularity in the metal's behaviour.

He went on with his experiments, trying to establish the relation between what he first called the 'particular' point and the size of the grains that make up the structure of steel. And again he was engrossed in observations, hypotheses and tests which finally led him to the discovery of another point on the temperature scale, at which another important change took place in the metal. To distinguish it from the first, or 'a', point, he called it the 'b' point. Later, a third, or 'c', point was discovered at which the metal changes from the solid to the liquid state.

The critical ranges (the critical points) discovered by Chernov (and called the Chernov points in Russia) are the cornerstones of the theory of the heat treatment of steel. Neither metallurgy nor mechanical engineering could today do without hardening, tempering, annealing and other forms of heat treatment.

How can we define these points that dotted the I's in the numerous discourses and disputes about the events occurring 'inside the steel as it softens and is heated'. This is what Chernov himself wrote about them: "However hard it may be, steel heated to below the *a* point doesn't harden, however rapidly it may be quenched. In fact, it becomes much softer and easier to work with a file. When heated to below the *b* point, the steel doesn't change its structure, no matter how rapidly or slowly it is cooled afterwards. As soon as the temperature of the steel rises to the *b* point, the bulk of the steel rapidly changes from a grained (or, generally speaking, crystalline) state to an amorphous (wax-like) state in which it remains on further heating to its melting point, or the *c* point".

Chernov's findings had valuable practical applications. The *a* point enabled metallurgists to determine the hardening temperature of steels correctly, and the *b* point proved a reliable guide in the ways of changing the structure of the metal. If a steel article was to have a fine-grained structure assuring high mechanical properties, the metal should be heated to or slightly above the *b* point and then rapidly cooled, or quenched.

Chernov's discovery had an important impact not only on the Obuhov Works which was thus able to eliminate spoiled products, but on all of world metallurgy: it laid the foundation for a new science, metal science, or physical metallurgy. Chernov may justly be called its father.

In the subsequent years Chernov worked a good deal on the solidification of steel and the ways and means of improving the quality of steel ingots. Those were extremely important matters: the closing decades of the 19th century saw an explosive growth in the large-scale manufacture of cast steel, but little was yet known about the events that take place when large quantities of molten steel are teemed and large ingots solidify. As he worked on his theory of ingot structure, Chernov gathered a large collection of iron and steel crystals. Aware of the scientist's passion, one of his disciples presented him with a king-size crystal he had found in the stockyard of an iron and steel works. Grown in the shrinkage pipe of a 100-ton steel ingot, the crystal tipped the scales at close on three and a half kilograms and was thirty-nine centimetres long. If we recall that ordinary steel crystals are not more than a few millimetres in size, we can readily imagine its scientific value for the scientist.

In his studies of solidification and ingot structure, Chernov identified the mechanisms by which dendrites, or tree-like crystals, are formed, how steel solidifies, and formulated quite a number of practical recommendations. He firmly believed that "the strength of unforged cast steel is in no way lower than that of the forged one, provided they are the same in constitution", and suggested how the desired fine-grained 'constitution' of steel could be assured.

Following up the ideas of Anosov who had unravelled the mystery of damaskene mainly by trial and error, Chernov was also able to disclose it, but from a scientific point of view. As early as 1869, he produced at the Obuhov Works an ingot of damaskene steel and worked it into two dagger blades: after etching, they displayed a clear wavy pattern.

The scientist summed up his views in a report, "Studies Related to the Structure of Cast Steel Ingots", which he read at a meeting of the Russian Technical Society in 1878. His report was of no less a value for the steel-making art than his discovery of the critical points.

Chernov stayed with the Obuhov Works for nearly a decade and a half. Through his illustrous and multi-faceted effort, the Works became, according to Academician A.A. Baikov, a prominent Soviet metallurgist, a veritable academy of scientific knowledge in metallurgy. Nevertheless, the remarkable scientist who had brought world fame to the Works was forced, in 1880, to leave it at the prime of life and full of creative plans.

The reason for this lay in the highly strenous relations between Chernov and General Kolokoltsov, Chief of the Works. A typical courtier and a personal friend of Czar Alexander II's, the general was intolerant towards any manifestation of initiative by his subordinates and disapproved of Chernov's research and social views. Made the head of a large works by fate's whim, the general could often be heard saying that the Works was not a place for science. Could he find a common language with a man who firmly believed that a works was unthinkable without science?

Nor could the general realize that he was an eye-witness of the history of metallurgy in the making and that a new division of science was born in his shops, offering an unprecedently deep insight into the inner workings of steel. Nor unlike Herostrate who burned, in the 4th century B.C., the famous temple of Artemis in Ethes and thus found his way into history by the backstairs, Kolokoltsov made himself 'famous' by turning Chernov's stay at the Works into a veritable hell. As the scientist later recalled bitterly, "I had to cede to the brute force of circumstances and to leave not only my research at the Obuhov Works but the steel-making art in general".

The remarkable Russian metallurgist couldn't however give up the steel-making art for ever, although he spent several years after he had left the Obuhov Works as a prospector for rock salt deposits in the south-west regions of the country. (He was interested in rock salt crystals as well.) When, in 1884, he came back to St. Petersburg, he took up a job with the Marine Technical Committee and the Ministry of Railways. Several years later, he was appointed Professor of Metallurgy at the Moscow Academy of Artillery and held the chair there for three decades.

Chernov applied his wealth of knowledge to many problems of metallurgy. During his service at the Obuhov Works, he made important improvements in the Bessemer process. Later he came up with the bold idea of making steel directly from iron ore. His writings are abundant in other interesting ideas bearing on the mechanical working of steel. He was the permanent chairman of the Metallographic Commission within the Russian Technical Society, the life-long honorary chairman of the Russian Metallurgical Society, an honorary vice president of the British Iron and Steel Institute, an honorary fellow of the London Royal Society, and an honorary member of the American Institute of Mining Engineers. He carried so much weight with the world community of metallurgists that he was elected to a jury of experts at many World Exhibitions.

Speaking before an expert commission in 1900, Paul Montgolfier, an influential French metallurgist, said: "I take it my duty to declare in public, in the presence of so many connoisseurs and specialists, that our works and all of the steel-making art owe their state of development and success to a marked extent to the effort and research of the Russian engineer Chernov. I invite you to express to him the sincere thanks and gratitude of all the metallurgical community".

In 1916 Chernov fell ill and had to move to Yalta for a cure. There, he spent the closing years of his life and lived through all the hardships of the Civil War in Russia and the foreign invasion. Informed that the outstanding metallurgist was living in poverty in the Crimea, the British government instructed the commanding officer of a mine-laying ship in the Black Sea to go to Yalta and to invite Chernov to sail on board his ship to London. The Navy officer did as told, but Chernov refused to move to England where he would have had all the good things of life, a cure, and a quiet job. He chose to remain in Russia.

Chernov died on the night of January 1, 1921 at the age of eighty-two. There is a cast-iron slab at the Old Aut Cemetery in Yalta where Chernov is buried. It carries the inscription: "Father of Metallography. Precursor and Head of a New School of Metallurgists. From the Russian Metallurgical Society to Its Honorary Chairman".

Chernov's life and activities have been highly praised by Soviet metallurgists. As Academician A.A. Baikov, one of his disciples, said once: "Chernov was a great genius of science who brought on a veritable revolution by his remarkable research. In his significance to metallurgy, Chernov may be compared to Dmitry I. Mendeleyev with regard to chemistry. Much as chemistry will steer the course mapped out by Mendeleyev, so metallurgy will develop in the direction predicted by Chernov".

The Twentieth Century Has Its Say

The Start of a New Age

The Itinerant Knight at the Crossroads — The Big Puzzle — A Job of Work — The 'Goat' on the Parquet Floor — Taming of the Sow — Valuable Trophy — The 'Academy' in the North — The Dream of the Metallurgist — The Professor and the Student — The Milestone — The Minister Makes Steel

By the turn of the century, the metallurgy of iron had taken a well-defined shape. The advent of processes for the large-scale production of cast steel had ousted both the bloomeries and the puddling furnace. The only exception was the crucible process giving steel of good quality, which still remained on the metallurgical scene, but could no longer claim a leading role.

The manufacture of steel, the primary product of ferrous metallurgy, involved basically two stages: the iron-making stage and the steel-making stage. The first stage used blast furnaces which turned iron ore into pig iron. During the second stage, this pig iron in company with steel scrap was smelted into various grades of steel. On leaving the blast furnace, the pig iron, like the fairy-tale knight at the crossroad, had the choice of any one of three roads: to the open-hearth furnace, the converter, or the electric furnace, depending on technological or economic factors.

The steel making plant at the disposal of metallurgists at the time enabled them to make a broad gamut of steels widely differing in properties. In short, both the blast furnace and the steel-making 'trio' suited metallurgists well, and nobody thought of devising anything new. Rather, there was a desire to get to the root of the events that happen in the making of pig iron and steel, to learn all the fine points of the processes in use, and to unravel what mysteries of the metal-making art remained still hidden. For this reason the end of the 19th century marked in effect the advent of a new age—that of an in-depth scientific quest into, and engineering improvements of, metallurgical practice.

The biggest puzzle of all, even for top-rank metallurgists, was perhaps the blast-furnace process. Scientists in many countries made attempts to find an answer to it. The first to lift a little the veil of mystery wrapped around the conversion of iron ore to pig iron was Mihail A. Pavlov, a Russian blast-furnace expert, later a prominent scientist and a member of the Academy of Sciences.

Pavlov chose to be a metallurgist back in his student years at the St. Petersburg Mining Institute. This happened during the summer of 1884 when he was doing his practical assignment at an Iron and Steel Works in Yuzovka (now Donetsk). The engineer-to-be took special interest in the blast furnaces with their flame raging inside day and night.

In his book, "The Reminiscences of a Metal-Maker", Pavlov recalls a talk he once had with John Huges, the son of the Works' owner:

"Why is it that you come to the blast-furnace shop so often?" John Huges asked me one day. "Do you really like it there?"

"Yes, I do".

"Why?"

"Because others don't understand and don't like the blast-furnace art".

"Is that so?"

"Yes, it is. You, too, have said once that nobody—not a single engineer, not a single master, and not a single professor—has the slightest idea of what goes on in the blast furnace. And the furnace needs guiding!"

"But you aren't going to do that, are you?"

"Why not?"

"He looked at me and smiled. But he was polite in his answer: "That's a job of work".

"Yes, it is," I answered.

That 'job of work' was to become the cause of Pavlov's life. He made valuable contributions to blast-furnace practice, perfected the furnace design, and improved the thermal working of the furnace. Re-designed as he advised—and this was done at many iron works, the blast furnaces usually produced more pig iron and of a much better quality at that. His fundamental work, "The Metallurgy of Pig Iron", on which he worked a good half of his life (he died in 1958 at the age of about ninety-five), has been a book of reference for many generations of metallurgists.

While Mihail Pavlov was more of a blast-furnace theorist tending to tackle all problems from a scientific position, Mihail K. Kurako may be called a true practical blast-furnace virtuoso who is justly ranked among the most brilliant figures in the history of Russian metallurgy.

Kurako was born in 1872 into the family of a Byelorussian landlord, a retired colonel who had fought at Sevastopol during the Crimean War. The boy was fairly well educated at home and knew French perfectly. His father planned a brilliant career for his only son, but the boy had a distaste for the rigid discipline and lack of freedom that existed at educational institutions at the time.

An unruly boy who would often express his protest against the discipline of the cane in a child's naive way, he had a fairly long record of punishments by the time he was fifteen: he had been expelled in turn from the Corps of Cadets, two classic high schools, and a technical high school. The last time it was a farming high school—the boy had 'expelled' himself by striking the principal, a petty tyrant and a wilful and stupid person when he had the boy lashed with birch-rods unjustly for a prank. The boy fled from the school and from his home.

Following the advice of his foster brother, Kurako went to Ekaterinoslav (now Dniepropetrovsk) and took up a job at an Iron and Steel Works. At first he was a sample-runner—he carried samples of pig iron to the laboratory. But an unwritten law had it that a sample-runner should also serve engineers: bring cigarettes, serve tea, and do a host of other chores. The proud young man didn't want to be an errand boy and asked his superiors to transfer him to the job of a barrow-pusher.

That was an extremely arduous job. Twelve hours a day had he to push his 'goat', as the barrow was nicknamed locally, filled full with charge materials for the blast furnace. But as if to make up for it, the boy was next to the blast furnace all the time, listening with interest to the hollow rumble in its huge belly. He eagerly caught every word the foreign engineers and masters exchanged in French, not suspecting a bit that the ragged barrow pusher could understand what they were talking about.

One day, there was a visitor to the works—he was d'Horizont, director of a French bank and one of the actual owners of the Works. Accompanied by a numerous retinue on a round of the shops, he stopped at the ore pile where the young Kurako was loading his 'goat'. His strong muscles stood in solid relief against the rusty ore dust covering his sweaty body.

"This monkey is admirably good at his work, isn't he?" d'Horizont said in French, not suspecting the Russian understood what he was saying.

That was more than enough for Mihail's ego. He stood erect, threw his shovel aside, turned around his barrow, and pushed it hard at his offender. The Frenchman, frightened a lot, jumped aside, but the heavy 'goat' steered by the young man's strong hands followed the VIP all over the ore yard until the man was pressed against the ore pile. Quick as a monkey, the bank director climbed atop the pile. Coming to a stop in front of the pile, Kurako explained in perfect French and with an unconcealed jeer that everything had happened because of the 'parquet' (as the flooring of the ore yard was called) which was covered so much with potholes that he hadn't been able to steer his "goat" properly. The incident was hushed up, and the ore yard came by a new flooring.

The fiery might working miracles in the blast furnace attracted the young man with an ever increasing force. A great engineering talent was awakening in him, imperiously calling for a worthy application. Although he had no formal education, Kurako learned all the secrets of the blast-furnace art very soon and rose to the position of an acknowledged master. He always longed for ever harder and therefore more challenging tasks. In 1898 he moved to Mariupol and took up a job at the newly built Iron and Steel Works equipped with American blast furnaces, the largest at the time. It was there than an event took place, which was to make Kurako famous all over Russia.

Quite unexpectedly the blast furnaces developed some trouble and their output took a plunge. Huge 'sows'—bulks of fused ore and solidified pig iron—were growing in the furnaces. There seemed to be only one way out—to stop the furnaces, to break them open, and to remove the sows. The company was facing a major loss, and the owners had no other choice than to accept the fact.

Several days before they were to stop the furnace growing the biggest 'sow', Kurako came into the director's office.

"Who are you and what do you want?" the director asked roughly.

"You must know me", Kurako answered in French in a "thee-and-thou' manner. "I'm the second furnace's attendant. They say the first furnace is about to be pulled down?"

"Yes, it is, but that's none of your business".

"Don't pull down the furnace".

"It must be pulled down with a 'sow' that big!"

"The 'sow' can be melted".

"Melted?" The director grinned. "Isn't it you who are going to do the thing?"

"Right, it's me. Let me have the furnace for a couple of days".

The director looked over the furnace attendant with unconcealed curiosity. He could feel in the lean, handsome fellow some power which commanded trust. "After all, you can never tell", the director thought to himself. "It may so happen that this bum will save the furnace. If so, they will pay me a fat bonus. One way or the other, I would lose nothing".

"How much do you want for the action? Will a 25-rouble banknote suit you?"

"The company would be happy to pay me a hundred times more, but I don't want money—what I want is a written testimony that I've melted a 'sow'".

Kurako and his helpers sweated over the furnace for several days on end, without so much as a wink of sleep. And they did save the furnace. The rescuer got his testimony on the company's stationary and with the company's seal affixed to it. It read that furnace attendant Mihail K. Kurako had been instructed to save a furnace with a 'sow' and that after three days' effort and through Kurako's skills the operation was restored to normal.

As Academician I.P. Bardin recalls in his memoirs, "The directors of many works were hunting for him as if he were a precious game. He was invited each time a grave accident had occurred, when all ways and means seemed to have been tried and failed to save the situation, and each time he worked miracles. Quiet and concentrated, he turned up at the head of his amazingly tight-knit team, got down to brass tacks at once and as often as not, put the conceited engineers, the eminent scientists, and the famed furnace operators in an awkward position".

But the owners of works were not alone in their hunt for Kurako: in the violent year 1905 Kurako who was active in the revolutionary movement was arrested and banished to the Arkhangelsk Province in Russia's north. While in exile, Kurako was busy with his self-education, reading books on chemistry, physics, philosophy, history and literature, and learning foreign languages.

In his book, "The Life of the Engineer", Academician Bardin recalls an episode which shows Kurako as a man with a good deal of optimism and sense of humor:

"Somebody once asked Kurako where he had been educated.

"I'm an alumnus of the Nikolas academy".

"In St. Petersburg?"

"No, in Arkhangelsk. I was its student for three years. An excellent academy. Czar Nickolas II personally had placed me there".

"Kurako paused and swept the audience with his bright eyes.

"It's the best university the government has ever established". Kurako laughed. "True, its uniform is not what you'd call a fancy dress—a prisoner's gray frock".

When his term at the 'academy' was over and Kurako was set free, he went back to Yuzovka to become very soon the superintendent of the blast-furnace shop at the Hughes Iron and Steel Works. As a man who never shunned manual labour, he did much to make the lot of the furnace operators easier. The superintendent knew well every workman, his family affairs, his needs and troubles. He helped many with money and never turned down a borrower. The workmen repaid him with their sincere love and were prepared to go through fire and water for him. Not a single family festivity could do without him, and he was the first with whom the workmen would share their joys and woes. On the other hand, no other superintendent at the Works was as strict and demanding as Kurako.

A talented man who had become a widely qualified specialist through self-education, Kurako dreamed of building in Russia a new type of works—large, with powerful, completely mechanized furnaces. He backed up his dreams with practical deeds: he devised unorthodox mechanisms and facilities for the blast furnace, improved its design and procedures, and worked on his plan of a new mammoth works.

Shortly before the October 1917 Revolution in Russia, a joint-stock company bearing the strange-sounding name of Kopikuz (which meant 'Mines of the Kuznetsk Basin') invited the famous blast-furnace practitioner to take part in the design work on the huge iron and steel plant the company contemplated to build in the Kuznetsk Basin, Siberia, rich in coal and iron ore. Kurako willingly accepted the invitation and soon moved to Siberia, accompanied by his friends and workmates.

Then the Revolution broke out, followed by the Civil War, and the project had to be shelved for the time being. As soon as the fighting had subsided, Kurako hurried back to his plans which were of special importance to the devastated country. But in Kuznetsk he fell ill with spotted fever, and the cruel disease broke the life of the supremely skilled master of the blast-furnace art in 1920. Kurako was buried at the highest spot of the site chosen for his unbuilt iron and steel works.

It fell to Ivan P. Bardin, a disciple of Kurako's, a remarkable metallurgist and one of the leaders of Soviet metallurgical science, to make Kurako's dream come true.

Born into a family of modest standing, Bardin entered the Chemical Department of the Kiev Polytechnic Institute in 1906. There he had an occasion to listen to V.P. Izhevsky, Professor of Metallurgy, whose lectures were a poetic and fascinating narrative of the blast-furnace process full of puzzles and mysteries. "What happens in the blast furnace", he would say, "is a fabulously beautiful thing. It is an unbelievably difficult, but highly sophisticated and joyful transformation of ore and rock to metal".

Highly experienced, Izhevsky was also an extremely kind and responsive man. As Bardin recalled later, "We, students, always were in need of money. The instruction fee at the Polytechnic was fifty roubles per half-year term, and that was a crippling sum for many a student. I was really frightened each time the day of payment was coming. My head would be in a whirl, and I wouldn't know what to do. Izhevsky had a list of students and knew perfectly well how badly any one was in need. Once he told me that in two days' time I would be expelled from the Polytechnic for failure to pay the instruction fee. Blushing with shame and stuttering, I explained to Izhevsky that I was in a money trouble only temporarily, that I would be able to raise the money in ten days at the most, and that it would be better for me not to attend lectures for the time being.

"Izhevsky protested. He said I could attend lectures and, patting me on the shoulder, said good-bye. The same day he paid the fee for me out of his modest income. He did so when he knew me only a half-year". Bardin remembered the event all his life.

At last the years of instruction were over, and the young man had a technologist's diploma in his hands. But where to apply for work? That wasn't an idle question for the young man, and not because he was in a position to choose. Jobs were hard to be had at the time,. and Bardin went across the Atlantic, to the United States in 1910. But even there, despite his diploma, he was only able to find the job of an unskilled labourer. As he recalled later, "We had to work ten to twelve hours a day in an exhausting heat. We worked strenuously, at the limits of our power, and fell to bed in the evenings like logs, unable to think of anything".

But it was there that Bardin's vocation and life were set: he learned first-hand knowledge of the steel-making art. As he wrote many years later, "Did I ever think of becoming a metallurgist? I was twenty-seven when I saw an iron and steel works for the first time. It struck my imagination. Metallurgy captivated me".

Bardin's stay in the United States was a short one: he had to do many things except making steel. "It's unlikely that I can learn anything as an engineer in America. Chances are I'd rather forget what I know" he thought and made up his mind to go back to Russia. Late in 1911, the British ship *Mauritania* carried him to Europe. What did his home country have in store for him?

With a letter of recommendation from Professor Izhevsky to back him up, Bardin went to the Hughes Works, among the largest in Russia, and took up the job of a designer in the rolling-mill division. It was then that Bardin was introduced to Mihail Kurako, Superintendent of the Blast-Furnace Shop. As Bardin recalled many years later, "My encounter with Kurako overturned all my life. Kurako not only made me an experienced metallurgist and a proficient blast-furnace engineer, but also taught me to think of high technology in metal-making".

In 1916, Bardin was appointed Superintendent of the Blast-Furnace Shop at the Enakievo Iron and Steel Works. It was there that he, already a matured specialist, met the October 1917 Revolution. Unhesitatingly, he sided with the new regime and placed all he knew and could do in the service of the working class and socialist industry. He was highly respected by and carried authority with the workers, and they unanimously elected him Chief Engineer of the Enakievo Works and Mines.

The year 1929 was an important milestone in Bardin's life: he was appointed to provide technical guidance in the construction of the Kuznetsk Iron and Steel Works, the first in the industrial development of Siberia. As he recalled later, "There is no denying, I felt proud and was full of joy. The iron and steel project was of special interest to me. An integrated iron-and-steel plant to be built along American lines in my country had been my dream all my life and the coveted goal for the engineer's soul of mine. I felt pride and joy because it had fallen to me to build a works in Siberia—a land which scared away many people with its severity and wilderness".

The giant project was launched when Siberia was in the embrace of a sever winter. Fires were burning on the site day and night, warming up the frozen ground. There was an acute shortage of labour force and machines, but the people who had come there from all over the huge country were digging trenches in the stone-hard ground, laying foundations for the furnaces, and erecting buildings for the shops in the face of the sharp frost and the raging wind. The motive power behind all the activities was Ivan P. Bardin.

It took just over two years for the Kuznetsk builders and metallurgists to produce the first heat of Siberian pig iron.

As the technical supervisor of the giant Kuznetsk project, Bardin showed he was an outstanding planner and manager, a man who could tackle the most challenging problems of metallurgical theory and practice. He was one of the new generation of engineers who combined the knowledge of a scientist, the foresight of an innovator, and the inspiration of a creative mind. The Soviet Academy of Sciences found Bardin's record of accomplishments extremely valuable and important for the country: in 1932 he was elected a Member of the Academy. It was the first time that the Academy elected not an armchair scholar but a practical scientist who had found his way inside the Academy's walls from the din and roar of a works' everyday activity and who had proved the worth of his scientific views with mammoth iron and steel works and with millions of tons of iron and steel the country needed so much.

To Bardin himself the news of his election to the Academy came as a surprise: "I was taken aback when I heard the news. I'd written no papers of importance in my life". That was true: he had not a single treatise on the subject to his credit, but there were hundreds of drawings of the huge iron and steel works, the blast and open-hearth furnaces built under his guidance, and also the pig iron and steel made at the Kuznetsk Integrated Works.

In the same years, another 'firstling' of Soviet metallurgy was taking shape at Mount Magnitnaya in the Urals. In the summer of 1929, the first builders' tents were pitched in the Ural steppe and before long a whole 'tarpaulin town' could be seen standing there. Thousands of people had come there to build the works. Many of them knew nothing of the trades needed, but they had what seemed to be far more important for a large and complex project under extremely adverse conditions—perseverance, steadfastness, and the drive to see things done in spite of any hardships.

Some specialists were, however, highly sceptic. One of the older generation, for example, worked there for some time but didn't take root, so to speak: he didn't like much of what he saw and believed the very idea of building a huge works in the Ural backwoods, away from any potential users of iron and steel, was an outright blunder. When he was leaving the site, the engineer told his piece of mind to the project's management: "If you built a similar works in the heart of the Sahara Desert in Africa and carried the metal from there to Russia on camels, even then it would cost half as much".

Well, the first steel from Magnitka, as the huge project was lovingly called, did cost a lot, but the unfortunate prophet was deeply wrong. Before long Magnitka came to make the country's and, indeed, the world's cheapest steel of excellent quality—the steel that proved its worth during World War II.

But the war was still several years off, and the country went on with its challenging projects in the Urals and Siberia, at the rapids on the river Dnieper and in the steppes of southern and central Russia, on the shores of the Aral Sea and in the Caucasus, on Lake Balkhash and in the Monche tundra: major metallurgical works and shops went up everywhere to give steel and aluminium, copper and nickel, lead and zinc to the country.

People, too, were rising in step with industry. The years of the early five-year plans saw the emergence of a whole constellation of brilliant metallurgical engineers who were to stand at the helm of Soviet industry before long. Perhaps, the most brilliant among them was Ivan F. Tevosyan, one of the master-minds of Soviet high-quality metal-making.

In 1929, after he had graduated from the Moscow Mining Academy, Tevosyan was sent to Krupp's works in Germany where the young engineer was to learn all that was new there. As a rule, the foreign metallurgists visiting Krupp's works would be content with the role of an observer. But that didn't suit Tevosyan. Soon after his arrival, Tevosyan asked Krupp for his permission to work at the furnace for several months. Krupp granted his permission, saying that "Johann Tevosyan deserves the right owing to his exceptional diligence, talent and brilliant knowledge of the theory of steel making".

making shop he saw a master obviously violating the approved procedure. When Tevosyan reproved him, the man muttered in response: “I’ve seen a lot of advisers, but not a single workman!” The minister took the master’s place and carried the heat to the end ‘by the book’. The master surely remembered the lesson all his life.

The country was engaged in a multitude of projects, and it needed steel—not only to make machines, automobiles and tractors, and to build railways and factories. It needed steel for tanks, guns and airplanes—the steel that was to become the country’s reliable shield against the treacherous enemy that was already standing at its threshold.

When the world heard the first salvos of what was to become the Great Patriotic War to the Soviet People, the country turned into one large smithery making steel and forging an indestructable shield and a formidable sword. As a poet said, “The country didn’t sleep a wink, standing its watch at the furnace’s brink”. That is true: the fiery stream of steel was flowing day and night, bringing the country closer to the long-awaited Victory Day.

Different Fates

The Trouble-Maker — A Complimentary Supplement? — Reappraisal of Values — Less a Trump Card — Oxygen Injections — The Open-Hearth Furnace Afire? — The Quiet Life — Events in the Emptiness — The Secret Under Seven Seals — The Academician’s Error — Early Ripening Again? — The Beauty from the North — Changes to Come — The Unanswered Question

Smelting furnaces are not unlike people—each has a fate of its own. Some serve for a long time, while others die young; some live a quiet life, while others are destined to see rises and falls.

steel-making process was not new. ed out the advisability of adding oxygen to the air used to blow the molten pig iron in the converter. As he believed, "This should substantially raise the temperature of the metal, on the one hand, and to cut down the duration of the process and the requirements for the driving force, on the other, because the air blower could then be scaled down in proportion to the amount of oxygen added".

That was true. Any metallurgical reaction needs oxygen, and its percentage in air is not at all high—a mere twenty-one per cent. Because of this, the air blown through the converter carries nearly four parts of nitrogen, by volume, as a 'complimentary supplement' for every part of oxygen actually needed. But is it actually a 'complimentary supplement'? As it leaves the converter the nitrogen carries off with it a good deal of heat which is thrown to the wind, both literally and figuratively. Also, since the oxygen that takes part in the chemical reactions is heavily diluted, their rate is well below the theoretical figure. But that is no end to the troubles stirred up by nitrogen: it has enough time, during the blow, to leave traces impairing many of the steel's properties.

Why is it then that metallurgists reconciled themselves with the situation like that for decades? The answer is simple: oxygen was very hard to come by in sizeable quantities because there was no commercial process for the separation of air into its constituent gases yet. It was only after sufficient progress had been made in many countries in the field of low temperatures (or cryogenics, as it is scientifically called) that machines could be built to liquefy atmospheric air and to separate oxygen from it. Now metallurgists could reckon on its assistance.

In 1933, Nikolai I. Mozgovoi, a Soviet engineer, made his first experimental attempts to blow the molten pig iron in the converter with technical-grade oxygen. The results seemed encouraging, and three years later he took out an inventor's certificate

In 1940, as the USSR Minister of Ferrous Metallurgy, Tevosyan recalled the time he had spent at Krupp's works: "I have had an opportunity to see how major industrial executives are trained abroad. Nearly everyone starts by working, for some time, as a workman—even the sons of plant owners! Why is it, it would seem, that the son of an owner of a substantial packet of shares should put on overalls and go to work on the shop floor? But unless he has learned the manufacturing process personally and to the minutest detail, any specialist would have to ape the master and be his captive".

Tevosyan himself had more than once to do as he had used to as a young man and to make steel with his own hands. Once he was on an inspection tour of an iron and steel works. In the steelmaking shop he saw a master obviously violating the approved procedure. When Tevosyan reproved him, the man muttered in response: "I've seen a lot of advisers, but not a single workman!" The minister took the master's place and carried the heat to the end 'by the book'. The master surely remembered the lesson all his life.

The country was engaged in a multitude of projects, and it needed steel—not only to make machines, automobiles and tractors, and to build railways and factories. It needed steel for tanks, guns and airplanes—the steel that was to become the country's reliable shield against the treacherous enemy that was already standing at its threshold.

When the world heard the first salvos of what was to become the Great Patriotic War to the Soviet People, the country turned into one large smithery making steel and forging an indestructable shield and a formidable sword. As a poet said, "The country didn't sleep a wink, standing its watch at the furnace's brink". That is true: the fiery stream of steel was flowing day and night, bringing the country closer to the long-awaited Victory Day.

Different Fates

The Trouble-Maker — A Complimentary Supplement? — Reappraisal of Values — Less a Trump Card — Oxygen Injections — The Open-Hearth Furnace Afire? — The Quiet Life — Events in the Emptiness — The Secret Under Seven Seals — The Academician's Error — Early Ripening Again? — The Beauty from the North — Changes to Come — The Unanswered Ouestion

Smelting furnaces are not unlike people—each has a fate of its own. Some serve for a long time, while others die young; some live a quiet life, while others are destined to see rises and falls.

Until about the mid-20th century, the bulk of steel had been made by the open-hearth furnace. The electric arc and induction furnace would only make special grades of steel for critical applications. The Bessemer converter, once everybody's favourite, had now to be content with a modest role indeed: it was in use only in a few countries where some specific conditions prevailed, such as the availability of iron ore best suited for the smelting of converter pig iron.

This traditional balance of forces was substantially changed by oxygen, the great accelerator of all metallurgical processes. Attempts to use oxygen-enriched air in the open-hearth furnace and in the converter were made as early as the 1920s and 1930s.

The idea of using a strong oxidizer in order to speed up the steel-making process was not new. As early as 1876 Chernov pointed out the advisability of adding oxygen to the air used to blow the molten pig iron in the converter. As he believed, "This should substantially raise the temperature of the metal, on the one hand, and to cut down the duration of the process and the requirements for the driving force, on the other, because the air blower could then be scaled down in proportion to the amount of oxygen added".

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In 1933, Nikolai I. Mozgovoi, a Soviet engineer, made his first experimental attempts to blow the molten pig iron in the converter with technical-grade oxygen. The results seemed encouraging, and three years later he took out an inventor's certificate for an ingenious modification of the converter process. This set off a search for a reliable commercial process, but the war soon broke out and retarded the solution of the problem, although research in the field went on both in and outside the Soviet Union.

A veritable boom in steel-making by the converter process began in the post-war years. In 1952, an oxygen steel-making process was tried on a commercial scale at an iron and steel works in Austria. Several years later converters using an oxygen blast appeared in some other countries, including the Soviet Union where the process was commercialized under the guidance of Ivan P. Bardin. The country's first oxygen-blown converter shop went into operation at the Petrovsky Iron and Steel Works in Dniepropetrovsk, the Ukraine, in 1956.

At that time, a re-appraisal of values was under way throughout the steel-making industry: specialists were aware that the converter now had a decisive edge over the open-hearth furnace, its long-time rival. Oxygen offered the converter process a package of weighty arguments enabling it to claim the leading part in steel-making. The weightest of all arguments was the high rate of production: while it took the open-hearth furnace several hours to complete a heat, the oxygen converter, even a very large one, needed just minutes. One more thing: the capital investments and the operating costs in the case of an oxygen-converter shop were substantially lower, and that made converter steel less expensive. The oxygen converter had beaten one more trump-card in the open hearth's hand: the nearly complete monopoly of re-working large quantities of scrap. The hot oxygen blast had raised the working temperature in the converter, and it was now no less successful at tackling this important economic task.

However, all of the weighty arguments would be worth nothing if the steel from the oxygen converter were poor in quality. But that wasn't the case: in the past converter steel had been inferior to open-hearth steel, not to speak of electric-furnace steel; now it could satisfy the most discerning customer. Blown with oxygen, the converter was now able to make even many grades of alloy steel—a factor which had once thought to be the privilege of the electric furnace. More than that: the oxygen converter came atop as the source of sheet steel for car bodywork.

It is no exaggeration to say that oxygen had blown a new life into the converter. The Bessemer and Thomas processes now belonged to the past, but their place was taken by the oxygen-blown converter embodying Henry Bessemer's ideas and the elements of the process devised by Sidney Gilchrist Thomas.

Oxygen-converter shops were going up in nearly all countries with a developed iron and steel industry, and quite a number of oxygen steel-making processes emerged, each adding something to the scale of manufacture and the range of products. At this writing, the oxygen steel-making processes account for over a half of the steel produced in the world. To all appearances, the converter which has taken over as the leader of the steel-making art is going to consolidate its positions still more.

And what about the open-hearth furnace? Couldn't oxygen have a wholesome effect on it as well? Attempts to use oxygen in the open-hearth furnace date back to the pre-war years and were followed up in the early 1950s. They have something to show for the effort put in: the output per furnace has increased, and less fuel is needed to carry out the operation. The proponents of the open-hearth process have tried to follow up the success: large open-hearth furnaces have been built, improvements have been made in the techniques and procedures, and natural gas has come to be used along with oxygen. But... It is becoming increasingly more evident that the open-hearth furnace is no match for the oxygen-blown converter. While the oxygen "breath" has given a new lease of life to the converter, oxygen "injection's" have only added a few years to the life span of the open-hearth furnace. Open-hearth furnaces are still in use in the Soviet Union and elsewhere, but their days seem to have been counted. The prevailing philosophy in the iron and steel-making industry is to replace them gradually with oxygen-blown converters and electric furnaces.

Before we part with the open-hearth furnace, however, we should pay it its due: it has been in man's service for over a century and has given many thousand million tons of high-quality metal in the meantime. Undoubtedly, it will occupy a place of honour in the history of metallurgy.

But to go back to our story. While the converter and the open-hearth were 'settling their issues', the electric furnace was steadily forging ahead. In the decades that had passed since the emergence of the electric steel-making process, the furnace was gaining in size and improving in design. The high temperature maintained in the electric furnace was enough to tame even the most refractory metals tungsten and molybdenum, and metallurgists came by an opportunity to make steels alloyed with any element.

Oxygen, too, made its bit in the advance of electric steel-making. Right after the war, trials were made at a steel works in the Soviet Union to blow in oxygen through iron pipes called oxygen lances. This innovation served to boost the output of electric furnaces and to cut down the consumption of electricity, electrodes, and some scarce alloying additions. The quality of the steel was improved as well, especially that of the low-carbon alloy grades. In the past, special effort had to be made so that the steel could get rid of the carbon continuously added to the arc furnace by its carbon or graphite electrodes. Now the carbon content could be conveniently kept down to an acceptable level owing to the strong union that oxygen usually makes with carbon.

This task is handled especially well by the induction furnace which has found a broad field of application in steel-making. In contrast to the electric arc furnace, it has no electrodes, and so there is no source of an increased carbon uptake by the steel. This is the reason why the induction furnace can make high-alloy steels carrying practically no carbon.

The 1950s saw important events take place in steel-making. They had an important impact on further advances in metallurgy as a whole and electric steel-making processes in particular. More important still, they marked the birth of a new school in steel-making. They were set off by Alexander M. Samarin, then a corresponding (later a full-fledged) member of the Soviet Academy of Sciences, and the events themselves took place in a nearly empty space or, more accurately, in a very high vacuum.

Back in the pre-war years Samarin and Novik, one of his co-workers, suggested that if molten steel was placed in a vacuum and isolated from the atmosphere, one could remove practically all the gases which the steel usually picks up during a heat and which have a detrimental effect on its quality upon solidification. That was an excellent idea, but it was far ahead of its time: it wasn't until the post-war years that the plant required to treat steel in a vacuum on a commercial scale was developed.

The vacuum processing of steel was tried on a commercial scale—for the first time in the Soviet Union and in the world—in 1952. A ladle filled full with molten steel was placed prior to casting in a vacuum chamber where the melt could get rid of the dissolved hydrogen, nitrogen and other objectionable inclusions in a matter of minutes. Soon a modification of the process was tried in West Germany. The vacuum-degassed steel was so high in quality that the process—in one form or another—soon found its way into practice at steel works in many countries—vacuum metallurgy had been born.

The idea of using vacuum in metallurgical processes proved very fruitful: in the wake of vacuum degassing of molten crude steel, a proposal was made to smelt steel in a vacuum. The proposal was accepted, and the works producing high-quality steel soon came by vacuum induction and arc melting and casting furnaces. An induction vacuum furnace differs from what takes place in a conventional induction furnace only in that instead of the atmospheric pressure use is made of high or even ultrahigh vacuum produced by powerful vacuum pumps. With a vacuum arc furnace, however, there is a fundamental difference: the furnace re-melts, or refines, the crude steel made in a conventional furnace, thus improving the metal's quality very markedly. That was the advent of a new and very promising venue of development in metallurgy: the refining of metals and alloys. (The same job can also be done by the electroslag, electron-beam and plasma processes to be discussed in the chapters that follow.)

Thus, the reader has been introduced to the steel-making 'trio': the converter, the open-hearth furnace, and the electric furnace. Now let's turn again to the blast furnace for its future has long been of concern to many metallurgical scientists.

It is hard to imagine today's industrial skyline without blast furnaces. These giants can be seen towering above the other structures of an iron and steel works from a large distance. But they are a far cry from the blast furnaces that were in use in Pavlov's and Kurako's days. Early in his career Pavlov, already familiar with blast furnaces, arrived at the Ural works where he was to take up a job. As he recalled later, "I went to the Works across the dam which rose above the site rather high. As I approached the Works, I looked against my will for the blast furnaces. They were nowhere to be seen. But I firmly knew the Works had two of them. The earthen dam ended in a slightly up-sloping wooden bridge leading to the nearest building. At the far end of the bridge I found myself on the service platform of the blast furnace I had been looking for in vain".

No one can miss today's blast furnace. It is a huge tower several dozen metres tall. Inside its belly, thousands of tons of ore and charge materials are continuously turned into pig iron. Loaded at the top, the charge moves downwards against the up-coming and penetrating fiery blast—extremely hot air driven under a very high pressure. A host of sensitive instruments keep a constant watch on the furnace's condition, and the dutiful actuators and mechanisms make the charge and the blast behave as they should under the process schedule.

The workings of the blast furnace were viewed as an enigma wrapped in a mystery for more than a century, but it was finally forced to part with its secrets. As Mihail Pavlov, already a Member of the Academy, justly noted, "Nothing can be seen in the blast furnace from the outside, but a good deal has become clear". Today the science of metallurgy may be said to have learned everything about the blast furnace.

An interesting event bearing out the point took place in Chicago in 1957 during Bardin's visit to an iron and steel plant. The chief metallurgist from the R & D department of the company that owned the plant, who accompanied the Russian, asked him how much pig iron their blast furnace could turn out when operated optimally. Bardin examined the furnace, found out the capacity of the air blowers, inquired about the quality of the charge materials, and answered with confidence: "Seventy-five thousand tons during a month of thirty-one days in cold weather".

The answer caused confusion among the plant's engineers because what they could tap from the furnace in the best of cases was around fifty-four thousand tons a month. They shook their heads in disbelief and thought that either Dr. Bardin had made an overestimate to impress them or his knowledge of the blast-furnace art, praised so high, had been overestimated. Still, they said they were prepared to follow his advice on how to raise the output.

When Bardin visited the same plant a year later, its chief metallurgist recalled the event and thought it would be good to check up on the guest's forecast. The plant's engineers told him the monthly production was short of seventy-five thousand tons. "What's the exact figure?" the chief metallurgist inquired. The answer was: "Seventy-four thousand five hundred ninety-two tons". The Academician's 'error' is a convincing proof that man is now in complete command of the once unruly and mysterious blast-furnace process.

Recent years have seen many signs of "early ripening" in metallurgy: the converters, furnaces and rolling mills have continuously been growing in size. The trend has affected the blast furnace as well. Only recently would a blast furnace two thousand cubic metres in size be looked upon as all but a wonder. Today, there are, in the world, quite a number of furnaces in operation, measuring four or even five thousand cubic metres in volume. And this is no limit. The most recent addition is the blast furnace built at the Cherepovets Iron and Steel Works in Russia, lovingly christened the Northern Beauty: it is over five and a half thousand cubic metres in volume. By way of comparison, the country's output of pig iron in the victorious year 1945 when all the blast furnaces in the Urals, Siberia, and the recently rehabilitated Donets Basin and Dnieper Valley were operating at full load was only slightly twice the amount that can be tapped from the Northern Beauty alone.

The staff of this unique blast furnace includes a team of microcomputers which control close on fifty process variables. The arduous job of opening and stopping the iron tap-hole and the slag notch has been relegated to remote manipulators. The powerful ventilation systems remove all of dust from the blast-furnace shop, and the electrostatic precipitators, or dust catchers, take care of the environments. The granulators turn slag into a valuable feed for the cement industry. In short, the Northern Beauty is the perfection itself in many respects.

Does it mean that the blast furnace, despite its venerable age of many centuries, is doing well and, in contrast to the open-hearth furnace, has no grounds for a worry about its future?

There is no simple answer. Undoubtedly, the blast furnace will for some time hold its ground in iron-making, but its future can hardly be taken as cloudless. As Professor R.D. Richardson, an English metallurgist, thinks, the trouble with the blast furnace lies in the fact that it produces a product we don't need. We don't need iron saturated with carbon; we need steel, and the union of the blast and open-hearth furnaces is not the most direct way to make it. But the shortest way is not the most economical one in many metallurgical processes, the professor notes.

Still, many specialists are of the opinion that the fate of the blast furnace is sealed: sooner or later the classical two-stage method of steel making will give way to a process using no blast furnaces, in which steel will be extracted from ore directly, with no pig iron made in between. But how soon will this happen?

The Search Goes On

Another Trouble with the Blast Furnace — Among the Cabinets and in the Corridors — The New Stories of Old Oskol — Swaping an Awl for a Brick of Soap? — Fewer Troubles — The Cascade of Steel — In Bessemer's Footsteps — The Turn of Good or Bad Luck? — Filling in Detail — On the Banks of the Dnieper — Guilty without a Guilt? — Every Cloud Has a Silver Lining — Triumph — Tricks in the Ladle — Montezuma's Gift — When the Fortress Won't Surrender — The Untrodden Path — Strained Relations

That the blast furnace makes a 'wrong' product is not the only of its troubles. Another trouble is that it needs coke—a vital item in its diet. Yes, the very coke whose invention was an important milestone in the progress of iron-making in the early half of the 18th century.

That's true: coke has played a key role in the making of blast furnace practice. It was coke that set the blast furnace on its 'feet', we might say. It is coke that has been supplying the blast furnace with 'nourishing' food. The situation suited the metallurgists quite well for a long time, but gradually the blast furnace's horizon has come to be overcast with what might be called coke clouds.

What is the matter?

The reader surely knows that coke doesn't occur in Nature. It has to be prepared from coal, and not just any grade of coal, but from one capable of coking. The reserves of such coal are, however, limited and they become ever more scarce and costly to work from year to year. Also, it takes a good deal of time and effort to make coke even from a coking coal, and quite a number of by-products are left over, not at all with the odour of perfumes.

Lest they should find their way into the atmosphere, one has to provide gas-cleaning facilities, all of them expensive but likely to break down quite often.

The expensive coke is a very important item on the list of costs of pig iron. That is why blast furnace operators have always been trying to cut back on coke by replacing it, at least in part, with natural gas, pulverized coal, and residual fuel oil. But isn't it possible to do away with coke and with the blast furnace altogether?

The question has tantalized scientists since long. The promise of making iron without coke intrigued D.K. Chernov. Late in the 19th century he proposed an unorthodox shaft furnace that would make low-carbon iron and steel instead of pig iron. Unfortunately, his idea wasn't destined to materialize. Some fifteen years after he had made his proposal, Chernov wrote with bitterness: "Exasperated by the usual sluggishness of our private works, I applied to the Ministry of Commerce and Industry, hoping that it would give me an opportunity to try the process in a simplified form at one of the Crown's iron and steel works. But although the minister gave his consent twice, I ran into unsurmountable obstacles among the cabinets and in the corridors of the Ministry".

Dmitry I. Mendeleyev, too, was in favour of the direct manufacture of steel. As he wrote at the turn of the century, "I firmly believe that with time we will again be set looking for ways and means of making low-carbon iron and steel from ore directly, omitting the pig-iron stage".

Scientists and engineers in many countries spent decades looking for a technically acceptable process by which iron could be extracted from ore directly. They designed and built dozens of furnaces and other pieces of plant, but the solution that would unquestionably satisfy them all evaded them for a long time. Each time there would be some trouble either in the process itself or in the plant used, or in the quality of the metal thus produced. Also, none of the plans was sound economically. The search seemed to be heading for a blind alley, although there were a few small furnaces that could extract iron directly from ore in Sweden, Mexico, Venezuela and some other countries.

It wasn't until the early 1960s that acceptable designs of shaft units were developed and attracted metallurgists in many countries. After a careful study, it was decided to build a similar plant in the Soviet Union.

The site for the project was chosen not far away from Old Oskol, a city situated in the Kursk Magnetic Anomaly area, a veritable storehouse of rich iron ores.

Years have passed, and the buildings of the Oskol Electrometallurgical Integrated Works stand now amidst the steppe, a huge complex operating by a process other than the traditional 'ore-to-iron-to-steel' scheme. The new scheme has two stages. At the first, pellets of iron-ore concentrate carrying mainly iron and oxygen are charged into sixty-metre shaft units fired by natural gas, where they get rid of their oxygen and are turned into metallic pellets consisting of iron almost fully. At the second stage, the metallic pellets are charged into high-power arc furnaces which produce high-quality steel free from sulphur and other impurities always finding their way into steel from pig iron which in turn inherits them from coke.

What is then the advantage of the new scheme if it has two stages all the same? Is it worth while swapping an awl for a brick of soap, as the Russian proverb says? The answer is yes.

Above all, the new process does away with the expensive and scarce coke. The blast furnace which brings the metallurgist to deal with molten pig iron and slag is replaced with a simpler and more manageable process involving pellets which cause far less trouble than the molten streams. Nor ought we to forget that the pellet-handling units are practically clean for the environments while the blast furnace is not always averse from sending its gray clouds into the blue sky. Last but not least, the Oskol process turns out a steel of high quality, capable of serving for a long time and reliably under the most adverse conditions typical of modern technology.

Does this mean that direct steel-making units are to replace blast furnaces everywhere and very soon? Of course, not. Where the reserves of coking coal are as large, as they are in the Soviet Union, blast furnaces will remain in service for many years to come, and pig iron will therefore be the primary starting material for steel making.

That is why many scientists are busy improving the conversion of blast-furnace pig iron into steel ever more. One approach seems to replace the traditional batch processes with continuous steel making. As practice today has it, the operation of the converter, the electric furnace and the open-hearth furnace involves several steps between charging the starting materials and tapping the finished steel. However short the duration of a heat may be, it stands in the way of making the entire cycle a continuous process offering tremendous benefits, both technical and economical.

Metallurgists in many countries have of late been playing with the idea of truly continuous steel-making. The scheme proposed by Soviet scientists envisages a cascade of continuously operating reactors. The starting materials, such as molten pig iron, scrap, and metallic pellets continuously fed to the reactor would consecutively pass through all the stages of the cascade where, acted upon by oxygen and other reactants, they would turn to steel. Finally, instead of being cast into large ingots, the molten steel would be fed through a continuous casting machine from which a solid rod, bar or slab could be extracted by pinch rolls.

A continuous steel-making plant seems to be still some time off, although pilot units have been tried. In contrast, continuous casting machines have long been in service at many iron and steel works.

The idea to cast molten steel directly into finished products, thus avoiding large ingots, was first put forward by Henry Bessemer in 1885, but the attempts to translate the idea into practice didn't bear fruit. In the 1930s, a different scheme of continuous casting was advanced, where the molten metal was to be cast into pieces for subsequent working. At first, the scheme was used to cast billets of non-ferrous metals, chiefly aluminium, copper, and their alloys. In 1939 Siegfried Yunghans, a German engineer, was able to produce the ever first steel billet on the continuous casting machine of his own design.

In the Soviet Union, work on continuous casting machines was started under Bardin's guidance during World War II. In 1953, a pilot installation was put in operation at the Novo-Tulsk Works, and two years later, the first commercial installation was commissioned at the Red Sormovo Works in Gorky.

We can hardly find, in the metallurgy of the 20th century, another process that has influenced it as much as continuous casting has. Instead of casting molten steel into large ingots and of rolling the ingots into billets, there is only one operation by which liquid steel is produced into billets, slabs or bars directly, thus supplying the feed for the subsequent rolling operations. There is no longer any need for cast-iron moulds to take care off prior to teeming or for facilities with which to strip the ingots, that is, to remove them from the moulds after they have solidified. Nor is there any need for huge and expensive blooming and slabbing mills where large ingots are ordinarily rolled into billets and slabs. Nor have the ingots to be re-heated prior to rolling in soaking pits or re-heating furnaces.

As we can see, continuous steel casting has appreciably simplified and streamlined the manufacture of steel and cut capital and operating costs. But the new process has more than that to its credit: it has eliminated the scrap from cropping of ingots and has improved the quality of products. No less important, it has improved the working conditions and lends itself readily to mechanization and automation.

A good deal of progress in continuous steel casting is associated with the name of Alexander I. Tselikov (1904-1984), an outstanding Soviet metallurgist. As a boy, he wanted to be an airplane designer. When, in the early 1920s, he became a student of the

Bauman Higher Technical School in Moscow, his plan seemed eventually to come true: he was studying aircraft design. But, as fate would often have it, he was sent, after his third year at the School, to do his practical assignment at an iron and steel works, and not an aircraft plant.

As Tselikov recalled later, "To tell the truth, I wasn't particularly happy when I was told to go and do my practical assignment at the Dniepropetrovsk Iron and Steel Works. My strong wish was to make airplanes 'with my own hands'. But the Works struck me. I saw a firework of molten metal, the white-hot bars whisking two and fro between the rolls of the mill, and the sweating workmen who bent the bars by hand and guided them from one groove to another.

"Perhaps, it was my first impression of what I had seen that made me take a fresh look at my life plans. Yes, I wanted to be a mechanical designer. So could there be anything more challenging than to make machines that would relieve man of the dirty and hazardous job next to the molten metal? It was then that I made my final choice".

Yes, that was a turn of bad luck for Tselikov as a student, but it was a turn of good luck for Soviet metallurgy which soon acquired in him a talented specialist who formulated the basic theory of machine building for steel-making.

The principal line of business for Tselikov was rolling processes and plant. It was under his guidance that a whole range of truly unique rolling mills were developed, capable of turning out both traditional 'straight' products and unorthodox pieces such as spheres, screws, and gears.

But the remarkable scientist and engineer lived not by the rolling business alone. His interests went very wide indeed—from mammoth blast furnaces to tiny 'mini-plants' in the most critical industries. The Research and Development Institute headed by Tselikov for many years was the cradle of commercial foundry and rolling units used in non-ferrous metallurgy, the world's largest hydraulic press, and an unorthodox continuous steel-making plant comparable in production rate with the converter.

It was within its walls that the first steps were made towards making a reality Tselikov's idea of merging all links of the metal-making chain into a single continuous entity. As he believed, "We've reached a point where continuous steel making, continuous steel casting, and continuous rolling can be merged into a single flow".

An inexhaustible creative drive, the desire to be amidst the most urgent problems of the industry, and the knack of seeing far ahead were all among the features that distinguished Tselikov, an Academician and twice Hero of Socialist Labour. But his portrait would have been incomplete if we had failed to add one more touch: even in a very advanced age he could, like a youth, swim in the cold waters of Lake Baikal or across the river Dnieper during the spring flood. That was a feat, indeed, for as the Russian author Gogol says, "Not every bird can fly as far as the middle of the Dnieper".

Now that we've come to speak of this remarkable river, let's move in our minds to its banks, the more so that we have a sufficient reason to make such a trip: ancient Kiev is the home city for an institution that has been making many and valuable contributions to state-of-the-art high-quality metallurgy—the E.O. Paton Institute of Electroslag Welding, headed by Boris E. Paton, twice Hero of Socialist Labour and one of the biggest masterminds in many fields. It is in this Institute that a fundamentally new metallurgical process has been developed—the electroslag remelting (or refining) of metals and alloys, which has justly won recognition the world over.

This is how the remarkable process was invented. In the late 1930s, what we know today as the automatic submerged arc welding process was developed simultaneously in the USSR, the USA and, a bit later, Germany. Two materials are used in submerged arc welding, welding flux or, rather, slag, and consumable electrode wire. Incidentally, many people not acquainted with metallurgy or welding wrongly believe that slag is something unnecessary or even harmful. In fact, slag plays an extremely important role in metallurgical processes: it shields the molten metal from the harmful effects of atmospheric oxygen and nitrogen and absorbs all kinds of impurities like a sponge, thus cleansing the metal. Indeed, it is a scavenger for the metal, and makes it clean and healthy. This is the reason why slag is an indispensable participant in most metallurgical and some welding processes.

Soon after automatic submerged arc welding had been invented, Europe was caught in the flames of World War II, the cruelest of all calamities that have ever fallen upon mankind. It swept a sizeable part of the Soviet Union like a storm of fire, turning to ruins the cities, villages and plants it met on its way. Among them was the Zaporozhstal Iron and Steel Works, one of the country's firstlings. When Soviet troops recaptured Zaporozhye, they found heaps of debris, distorted metalwork, and fallen blast furnaces and hot-blast stoves.

It was in 1948, during the rehabilitation of the Zaporozhye Works that a seemingly minor event took place, which was to become the point of reference in the records of the electroslag refining process. Automatic submerged-arc welding machines were busy, making the shell of a blast furnace. The weld quality was excellent as always—in fact, as it used to be during the war when submerged arc welding was employed to make tanks. Repair work went on quietly and steadily, although the arc would go out at times. But the machines went on as if nothing happened. That could mean only one thing: even in the absence of an arc, electric current kept on flowing through the blanket of slag and generated enough heat to melt off the electrode. Unfortunately, the weld metal looked now like a steel stalagmite hanging between the edges of the plates without touching and, consequently, without joining them together.

The matter obviously needed an inquiry. Researchers at the Paton Institute carefully examined both the process variables and the weld metal. The welded steel was amazingly good: dense and free from sulphur, oxygen and other impurities. To all appearances, the slag was guilty.

The necessary adjustments were made, the machines resumed their work without a hitch, and the annoying accidents, it would seem, could well be forgotten. But the researchers couldn't give up on the excellent steel that had trickled through the blanket of slag. A tantalizing idea occurred to them to make a substantial ingot in the same way as the steel stalagmite had formed of its own accord.

Headed by Boris Paton and Boris Medovar, later a Member of the Ukrainian Academy of Sciences, the research team at the Institute set about to implement the idea. In 1952, the first test ingot was produced in an electroslag refining unit built at the Institute, and six years later a commercial electroslag furnace went into operation at a specialized steel works in Zaporozhye, intended to refine steel for the consumable electrodes used in the electroslag process.

The high quality of the steel, the relative ease of the process and the simplicity of the equipment combined to win an unprecedented reception for the electroslag process. It triumphantly spread all over the world. Britain and West Germany, the United States and Japan, Sweden and France weren't slow in buying the license for the use of the electroslag refining process at their steelmaking and mechanical engineering works.

Since then the process has continuously been improved, the electroslag furnaces have grown in capacity, and a whole range of furnace designs have appeared. Progress has especially been remarkable at the Institute of Electric Welding where the remarkable electroslag refining process (or ESR for short) was born. At this writing quite a number of ESR units are in operation both in and outside the Soviet Union, each capable of producing large ingots some two hundred tons in weight or castings of a shape solely decided by that of the mould where the molten steel gradually accumulates and solidifies.

Apart from ordinary ingots, ESR units can turn out 'sandwiches' of many layers of different metals or alloys. In fact, ESR units can make blanks cast to nearly their true shape, such as crankshafts, high-pressure vessels, and gears.

The scavenging action of slag is utilized in one more metallurgical process developed at the Bardin Central Research Institute of Ferrous Metallurgy, USSR. The process has to do with synthetic slags that are added to the molten steel in the ladle. The idea of the process which produces steel of an especially high quality dates back to 1925 when A.S. Tochinsky, Chief Engineer of the Ilyich Works in Mariupol, USSR, proposed to pour steel from the furnace into a ladle to which some quantity of specially prepared molten slag was poured in advance.

Tochinsky's idea was this: the stream of molten metal poured into the ladle would pass through the blanket of the lighter slag and would intimately mix with it. Because of this the area of contact between the two would increase appreciably, the slag would have a better chance to produce its scavenging action on the steel, and the metal's quality would thus be improved. The process didn't, however, catch on for some reasons. It wasn't until the early 1960s, after a good deal of field testing and debugging, that the refining of steel with liquid synthetic slags was adopted for use in open-hearth, converter and electric-furnace shops at some iron and steel works in the Soviet Union.

Some other promising processes of steel conditioning outside the furnace have been proposed. Basically they consist in that the steel making unit, which may be a converter, an open hearth furnace, or an electric furnace, doesn't produce a finished steel—what comes out of it is a melt whose analysis is very close to that of the desired steel. Obviously, it needs further conditioning, that is removal of objectionable impurities and addition of alloying elements. As with synthetic slags, all this is done in the ladle: the hot metal is blown with an inert gas such as argon or with a mixture of a gas and slag powder.

What are the advantages of what is often called ladle metallurgy? Above all, there is an impressive increase in the production rate of the furnace because all 'finishing' operations take place outside. Also, as the metal is vigorously stirred in the ladle, the chemical reactions are speeded up, the steel is better degassed, and the unwanted nonmetallic inclusions are removed more readily. This serves to improve the quality of the steel—a key objective sought by any steel maker. For it takes smaller quantities of a high-quality steel to meet the needs of mechanical engineering, civil engineering and other steel-intensive industries than a steel of poor quality.

There is still another process or, rather a group of processes, with which one can save on steel no less efficiently and rationally. This is powder metallurgy in which blanks and finished products are made by compacting metal powder charges and by sintering the green compacts.

When someone asked a great sculptor how he went about turning shapeless lumps into his masterpieces, the sculptor said: "That's very simple—I only chisel off what is unnecessary". Traditionally, mechanical parts are manufactured by 'chiselling off' the surplus metal from blanks. Sometimes blanks lose many times their final weight of metal as chips and other wastes. Powder metallurgy offers a different approach: a charge of metallic powder is compacted in a mould of the desired size and shape so that there is nothing to be 'chiselled off' later.

This process is among the most promising ones in state-of-the-art metallurgy and, *paradoxically, among the most ancient.* For example, archaeologists found in the tomb of Pharaoh Tutankhamen who flourished about 1350 B.C. a dagger decorated with powdered gold. There is some ground for believing that the Aztecs, the Inkas and other aboriginal inhabitants of America had known how to make jewelry from powders of noble metals well before Columbus discovered the New World. Anyhow, we know from chronicles that early in the 16th century Montezuma II, the last of the Mexican emperors, gave the Spanish conquerors as a gift to the King of Spain several platinum mirrors—well worked and highly polished sheets of platinum. But how did the Mexicans make them? It is not unlikely that they knew techniques which came close to the powder metallurgy of our time. For platinum melts at 1769°C, and high temperatures like that were reached by metallurgists a good deal later.

Powder metallurgy hasn't been used as widely as it should for centuries. This can be explained by several factors. Firstly, the need for it arose infrequently: people did well with other known processes. Secondly, equipment wasn't yet available to carry out the operations involved in powder metallurgy.

An important page in the history of powder metallurgy was written by Pyotr G. Sobolevsky, a remarkable Russian scientist and engineer. When, in 1826, he was appointed Head of the 'Joint Laboratory of the Department of Mining and Salt Art, the Mining Corps of Cadets, and the Chief Rock Pharmacy' in St. Petersburg, he and V.V. Lubarsky, a metallurgist, set about to devise ways and means of turning raw platinum into a malleable metal. The snag was that none of existing furnaces could heat platinum to or around its melting point. But, as mathematicians would say, that was a necessary condition for platinum to be cast into any desired shape. That was a hard nut to crack.

When a fortress can't be taken by a direct assault, other approaches have to be tried. That was what the researchers did. They filled an iron mould with platinum sponge (obtained by treating a suitable ore with some chemical agents), placed it under a screw press, compacted the sponge, raised the compact to a white heat, and applied a heavy pressure again. The metal succumbed: without melting, the sponge turned into a solid piece which couldn't be told from a casting. That's how the two researchers came upon a process which is being practised even today. Indeed, it lies at the basis of all powder metallurgy.

Sobolevsky's services were duly rewarded. At the suggestion of the Finance Minister, the Czar ruled that the scientist be paid, 'by way of an exemplary recompense' twenty-five hundred roubles a year over and above his salary 'so long as he remains in service'. As to the revived process, it was again practically forgotten before long because furnaces were built, capable of heating their charge to a fairly high temperature, so that platinum and other refractory metals could be cast into shapes by the more familiar foundry techniques.

This time the oblivion was a short one, however. The early years of the 20th century saw an explosive growth of electrical engineering which needed large quantities of tungsten, molybdenum, titanium and other highly refractive metals which melt at a temperature higher than the melting point of platinum. That was where powder metallurgy came into the picture again.

Indeed, powder metallurgy came to stay, and it is especially important in our time when the process has at its disposal all the machinery it needs for powder preparation, compaction, and sintering. As compared with casting, rolling, or machining, the manufacture of sintered products takes less time, floor area, and equipment.

Powder metallurgy produces materials which can be obtained with difficulty, if at all, by any other process, such as tungsten and titanium based sintered carbides, or pseudo-alloys of metals (such as tungsten and copper) which won't mix when molten, or copper-graphite, aluminium-alumina and other composites, or a long range of porous materials that have found many uses in state-of-the-art technology. Articles made by powder metallurgy are highly stable chemically and highly regular in structure—factors of important significance.

Powder metallurgy has a highly promising relative—spray metallurgy. Advanced research in this field is under way at the USSR Institute of Light Alloys headed until quite recently by Alexander F. Belov, a prominent metallurgist, Hero of Socialist Labour, and a member of the Academy of Sciences. Among his merits are a huge potential as an organizer, far-reaching intuition in technical matters, and the knack of pin-pointing and resolving the most crucial problems. He joined industry as a young man in the late 1920s and rapidly climbed the ladder from a shop's engineer to director of a works. As director of a works, Belov always drew upon advances in science. Later, when he was appointed head of a research institute, he steered its activities towards meeting the practical needs of industry. Age seems to have no reign over him: as he used to do as a young man, he doesn't look for easy ways, but follows unbeaten paths. Spray metallurgy is one of them.

What is new and valuable about it?

It has long been noticed that the rate at which a molten metal solidifies has a vital bearing on its structure and, in consequence, its properties. The longer the time during which solidification takes place, the coarser the grain, and this leads to a greater number of flaws in the metal's structure. Quite logically, what one is to do is to speed up solidification. But how can this be done in an ingot of many tons in weight?

The researchers fell upon the idea of making minute ingots—tiny metal particles, or granules, measuring just a few microns across. As we know now, by spraying the molten metal into granules it is possible to reach extremely high rates of cooling—tens or even hundreds of thousands of degrees per second. The granules thus obtained are free from any structural flaws—there is simply no room or time for them to develop. Now it remains only to bond them together into the desired shape. This is done by applying a huge pressure of several thousand atmospheres which turns the assemblage of granules into a monolithic dense mass. Critical parts made by spray metallurgy for gas turbines can stand up to temperatures greatly in excess of what can be endured by similar parts made of nickel alloys by conventional methods.

The manufacture of parts by powder and spray metallurgy leaves no wastes, and so it does no harm to the environments, in contrast to many other metallurgical processes. It must openly be confessed: metallurgists and chemists have won the unenviable reputation of polluting the environments. But while we oughtn't await favours from Nature, it is entitled to favours from us. One such favour or, more accurately, consideration for and care of Nature, of our home planet, is the use of low-waste manufacturing.

Fire Alone?

Treasures in Seawater — The Unforeseen 'But' — A Million Tons a Second? — Uranium from the Sea — The Profitable Bargain — The Division of 'Property'— Stone Eaters — Left-Overs from the Lord's Meal — Day and Night — Phantasy or Reality? — As If by Agreement — The Mysterious Fact — Migrating Impurities — Cold Instead of Fire

For millenia, fire has been man's principal helper in the extraction of iron, copper, lead, tin and other metals from ores, and the ores have always been coming from the only source of practically all minerals, including metals—the Earth's crust. The only exception is perhaps meteoric iron, but it usually finds its way into man's hands after it has travelled a lot in the expanse of the Universe and has come to rest on the Earth. Man has been spending a good deal of effort in attempts to find deposits of metallic ores on land while there has always been an inexhaustible treasury of gold, magnesium, sodium, chlorine, boron and other metals and nonmetals next to him—in the seas and the oceans.

Scientists have long known that sea water carries many chemical elements, but they were unable until quite recently to find a key to the treasury despite many attempts. The greatest lure among the marine treasures was of course gold.

It was Fritz Haber, a prominent German chemist, who was among those who were keen to extract gold from sea water. He began his search for a workable scheme right after World War I, driven by the desire to make it easier for Germany to pay its war contributions. In the eight years that Haber spent on his work he was able to achieve quite a lot: he developed extremely accurate analytical procedures by which he could detect a few thousand-millionths of a gram of gold in a litre of sea water and techniques by which he could build up gold's percentage about ten thousand times. The success, it would seem, was around the corner. But (this unforeseen 'but' tends to turn up at the last moment quite often), as a thorough analysis showed, the actual gold content of sea water was about one-thousandth of what Haber had expected to find. It was clear that the game wasn't worth the candle.

Over a half-century has passed since, and what once defeated Haber can readily be tackled at the present state of the art. Research in this field is underway in many countries and the ocean will sooner or later become an inexhaustible gold field.

But gold is not the only thing man is after. It's worth while trying to extract other metals from sea water, the more so that many of them, such as lead, zinc, copper, and nickel, are not very abundant on land, and their reserves are dwindling so fast that they may well be fully depleted in a few decades from now.

Some countries have already built offshore units for the extraction of magnesium from sea water. This is a small-scale activity but it holds a great promise. The reserves of magnesium dissolved in the seas and oceans are so great that even if we were able to extract it at the rate of a million tons a second, it would take us close on two millenia, or as much as has passed since the birth of Christ, to exhaust them completely.

In Japan, an idea has been put forward to build a plant that would extract uranium from sea water. The facility is to consist of an offshore array of nets treated with titanic acid and stretching for a total of eight kilometres. On passing through the nets, sea water will enter a reactor to be treated for the recovery of uranium dioxide. As the Japanese scientists responsible for the project believe, the uranium extracted from sea water will carry the same price as the one produced on land. The plant which is to be completed by the early 1990s will produce nearly a thousand tons of uranium a year.

Among the many processes used by hydrometallurgy, that is, the extraction of metals from aqueous solutions with the aid of suitable chemical agents but without resort to fire so traditional for metallurgy, is sorption, or the taking up of a substance in bulk by another substance. Most commonly, sorption technology uses ion exchangers, or solid materials capable of donating some of their ions to the solution in exchange for particular ions present in solution.

The ion exchangers currently in use are many and diverse, each being tailored to do a job of its own: some will take up gold, others platinum, still others copper, and so on. This profitable transaction offers a means of producing extremely pure metals or of separating any two metals closely resembling each other in properties and occurring together in Nature, such as zirconium and hafnium, tantalum and niobium, and the rare-earth elements. As Boris N. Laskorin, a prominent Soviet scientist, believes, "Ion exchange technology will soon take up the dominating position in all fields of hydrometallurgy and chemical processing".

As potent is solvent extraction, another process used in hydrometallurgy, based on the fact that many organic liquids will dissolve metals more eagerly than does water. These fluids, known as solvents, pull, as it were, the desired metal from an aqueous solution, and the metal is then freed from the solvent 'embrace' by distillation, evaporation, crystallization or in some other way. Using several solvents in succession, we are in a position to 'divide' all of the 'property' present in solution. One such application for solvent extraction is the separation of the short-lived radioisotopes of various chemical elements.

There is a very promising division of hydrometallurgy in which metals are extracted by bacteria. It is a well-known fact that bacteria play an important role in the turnover of matter in Nature. It has been found that some of fossil minerals owe their origin to bacteria. In his day, Academician V.I. Vernadsky took a very serious view of hydromicrobiology. In our time some of his ideas have found practical applications.

For the first time the technical community learned of 'metallurgically minded' bacteria at the beginning of this century. At the time, some of the copper mines in Utah, USA, were abandoned: their owners had flooded them with water, believing there was no copper ore left. When, two years later, the water was pumped out, it was found to carry several thousand tons of copper. A similar event happened in Mexico where ten thousand tons of copper were 'scooped' out of the abandoned mines which had been dismissed as hopeless.

Where does this copper come from? Now we know that for some bacteria the sulphur compounds of certain metals are a favourite nutrient. Since copper in Nature is usually combined with sulphur, these bacteria are not indifferent to copper ores. By oxidizing the water-insoluble sulphides of copper, the bacteria turn them into easily soluble compounds, and do that at a very high rate. While the ordinary chemical oxidation of chalkopyrite (a copper mineral) removes a mere five percent of the copper in twenty-four days, bacteria can leach out eighty percent of the element in just four days. As is seen, the bacterial 'labourers' do show a good performance, indeed.

True, the 'feat' was accomplished in an experiment under practically ideal conditions: the temperature was maintained at a comfortable value of 30 to 35°C, the mineral was finely divided, and the slurry was stirred all the time. However, there are quite a number of facts showing that the bacteria can be rather unpretentious. Known as chemolithotrophic, or 'stone-eating', they can do their job in the Polar region as willingly as they do in the Kola Peninsula.

Bacteria can come in especially useful at the final stage of a mine's operation: as a rule, as much as five to twenty percent of the ore is left in what is usually classed as a depleted orebody. It is not economically attractive, if at all possible, to mine the remainder by the usual techniques. On the other hand, the tiny servants of man can readily find their way to the copper and pick up all leftovers from the 'lord's meal'.

Bacteria may well be used to re-work spoil heaps. The copper mines at Cananea, Mexico, have accumulated close on forty million tons in their waste dump. Although their copper content is meager (hardly two tenths of a percent), an attempt was made to spray them with water from the mines and to let the water collect in an underground reservoir. The yield was three grams of copper from every litre of water. The operation brought in 650 tons of copper from 'nothing' in just one month.

Huge piles of copper-bearing muck can be seen towering next to the copper mines near Salt Lake City in the western USA. The piles have been turned to natural 'leaching vats' where the job is done by bacteria. The piles are sprinkled with acidified water, and this seeps through the bed of muck. This offers a happy opportunity for leaching bacteria to multiply at a tremendous rate—several million bacteria have been found to flourish in every gram of material sampled from the top of a pile. Owing to their activity, the solution picks up ever more copper and goes to traps from which it is transferred for processing. Over one-tenth of the copper produced in the United States comes from the bacterial process.

Bacteria are employed by some mines in the Soviet Union, too. The first pilot unit for the bacterial leaching of copper went into operation at the Degtyarsk copper deposit, among the largest in the Urals, in 1964. Here, the huge spoil heaps near the abandoned open pits and the ore dressing factory, accumulated during the many years of operation, had turned into a deposit of lean copper ore. It was there that 'stone-eating' bacteria were let to do their job. There could be no complaint about their diligence: many tons of copper were thus obtained. The bacterial extraction of copper at Degtyarsk is now a commercial activity. Bacteria are 'recruited' for work on a large scale at other places in the Urals and Kazakhstan.

Biometallurgy is a very promising venue. Already now underground leaching is the cheapest way of extracting copper: there is no need for miners working underground, or for plants to roast and dress copper ore. All that is necessary is done—willingly—by billions of tiny 'metallurgists' which, like elfs from fairy tales, work untiringly day and night, helping man produce the metal he needs.

According to research done at the USSR Institute of Microbiology, copper is not the only metal that attracts industrial bacteria. Their taste is broad indeed: they can handle iron, zinc, nickel, cobalt, titanium, aluminium, lead, bismuth and many other elements including the valuable metals uranium, gold, germanium, and rhenium. Several years ago it was proved that bacterial leaching could recover the rare metals gallium, indium, and thallium.

The techniques based on geomicrobiology substantially cut down the loss of valuable metals underground. An unquestionable advantage of microbiological processes is that several elements can be extracted at a time. For example, copper ores often carry sulphur, iron, gold, silver, cadmium, zinc, indium, rhenium, gallium, selenium, tellurium and some others which, with conventional technologies, usually go to a spoil heap. Bacteria won't just remove the principal 'value' of an ore—they will collect the other 'values' as well.

Bacteria are useful when it comes to hard-to-dress, or 'resistant', gold-bearing ores. Bacteria are well equipped to bring out gold finely dispersed in arsenic pyrite concentrates to raise the yield nearly ten-fold. Bacteria 'know' how to remove arsenic, a highly objectionable impurity, from gold or tin concentrates; the arsenic thus removed can then be used as a product in its own right. Bacteria hold special promise for the beneficiation of bauxites. To judge from trials, the bacterial digestion of aluminosilicates can markedly increase the extraction of aluminium.

Through bacteria, man can tap on a commercial scale the hard-to-get mineral deposits lying deep in the Earth's crust. After suitable bore-holes have been drilled, it would remain just to lower pipes to the required depth and to pump in a bacterial 'soup' so that it comes in contact with the ore-body. In passing through the ore, the 'soup' would pick up the metal (or metals) of interest and carry the trophy to the surface. There would be no need for mine shafts, fewer units would be required to work the ore at the surface, the cost of mining would be a tiny fraction of what it is today, and less money would have to be spent on treating the wastewaters and preventing atmospheric pollution. The large tracts of land now occupied by the mines and ore-dressing factories would be made free for other uses.

As Academician A.A. Imshenetsky believes, "The time is not far off when industry will be widely using microbes as active 'producers' of valuable metals. This would have seemed fantastic just two decades ago, but today man has learned how to guide and 'whip up' those invisible 'metallurgists'. In fact, uranium, copper, germanium and other metals are now being produced on a commercial scale at many places the world over by pumping bacteria-laden water into the mines abandoned because of ore depletion.

"Undoubtedly, microbes will make hydrometallurgy a leading industry towards the end of the 20th century. Bacterial cultures capable of oxidizing the compounds of sulphur and other elements will be among the most perfect and cheapest metallurgical 'agents'. Again, this activity can readily be automated".

Imshenetsky is a microbiologist. Isn't it possible that he takes a biased view of what bacteria can do for metallurgy and that we ought to be more conservative in our estimate of the future outlook for the new technology? However, his view is shared by Boris

E. Paton and Boris I. Medovar, both of them leading authorities in the electrical metallurgy of special steels and alloys: "There's every reason to expect that the future lies with biometallurgy. Through it man will be able to produce iron and other metals and, therefore, various steels and alloys of remarkable purity and quality on an unlimited scale and without detriment to himself and his environments. Biometallurgy needs no refractories, fluxes or fuels, and any chance will be eliminated for objectionable impurities (both solid and gaseous) and for nonmetallic inclusions to contaminate the product. All this will go a long way towards improving the service qualities of metals to a level we can now only dream about on the basis of what we have learned by testing tiny specimens made in the laboratory from ultrapure starting materials".

While bacterial metallurgists are learning their new trade, let's touch upon one more field of activity which has long been in use at works producing nonferrous metals. It has to do with the production or refining of metals by precipitating them electrolytically from aqueous solutions or melts. One example is the production of aluminium the world over by the electrolysis of alumina dissolved in fused cryolite. The electrolytic production of aluminium from clay was invented, almost at the same time but indepently of each other, by Charles Martin Hall of the United States and Paul-Louis Héroult of France in 1886. The history of science and technology knows quite a number of cases where two scientists made the same discovery in the same year, and the coincidence wouldn't have been worth mentioning but for the fact that Hall and Héroult were born in the same year 1863 and died, as if by agreement, in the same year 1914.

The essentials of their discovery remain the basis for today's aluminium industry, and this causes many scientists to rack their brains over a very mysterious finding. There is, in China, a tomb where General Chou Chu was buried in the early 3th century A.D. Recently, a few pieces of the metallic ornament on his tomb were analysed spectroscopically. What was found was so unexpected that the test was repeated over and over again. But each time the unbiased instrument read the same thing: the alloy used in the ancient ornament was eighty-five percent aluminium. But how could aluminium be possibly made in the 3rd century A.D.? For the only form of electricity, if any, of which man might be aware at the time was lightnings, but they are no good to take part in electrolysis. It remains only to presume that some other method of making aluminium was known in those far times, unfortunately lost to civilization in the course of centuries.

In addition to hydrometallurgy and electrolysis, metal-makers today widely rely on crystallization in the preparation of especially pure metals and semiconductors. Here they utilize the difference in composition between the solid and liquid phases. One example is the zone refining of antimony, an important starting material for the semiconductor industry.

The doping of germanium, one of the chief semiconductors, with just one millionth of a percent of antimony noticeably improves its 'business qualities'. But as a dopant, antimony must be pure to the utmost. This is where zone refining comes in as a way of making a chemically 'sterile' material.

This is done as follows. A long cylindrical ingot of ordinary, that is, not very pure antimony is placed in a graphite boat, and the boat is put in a quartz tube enclosed in an annular electric heater. As the operation goes on, the heater is slowly moved relative to the ingot, melting its various parts, or zones, in turn. As the zone left by the heater cools, the impurities it holds move forward to the next zone where the metal is liquid. This happens by a physical law which decrees that, as a molten or liquid material crystallizes, its impurities have no 'right' to solidify along with it—they must remain in the liquid phase. One instructive example is the ice covering the northern seas in winter: it carries almost no salts, although sea water is abundant in them.

As they gradually move along with the molten zone, the impurities finally reach the end of the ingot. This part is cropped, and the remainder—ultra-purified antimony—may be shopped to any customer, however discerning he may be. For critical applications, zone refining may be carried out more than once. It may be noted in passing that the ultra-purified antimony of Soviet manufacture, shown at the 1958 World Exhibition in Brussels, was found to be the world's best and accepted as a world standard.

Metal-makers today have at their disposal a wide range of diverse processes many of which have nothing to do with fire, the traditional symbol of metallurgy. In fact, there are processes which rely on cold, the antipode of fire. A team of British and American specialists have developed a process in which copper ore is leached with a solution of iron chloride, and crystals of copper chloride are separated by freezing them out of the 'pregnant' solution. In a reactor the copper chloride is reacted with hydrogen to form fine granules of metallic copper mixed with silicon oxide as impurity. Chemical cleaning with a salt solution leaves granules of pure copper. As you see, one of the important steps in this process is the action of low temperature on the feed.

Yet, high-temperature processes will dominate metallurgy in the nearest decades and, perhaps, centuries. Some of them will be taken up in the next chapter.

The Plasma Takes the Floor

The Metal-Melting Beam

A Beautiful Yarn or a True Story? — The Cloud-Covered Skies — The Right Hell — Where Would the Sea of Azov Go? — The Sun at Work — The Fiery Chariot of Helios — The Bombardment of the Metal — At the Mercy of Electrons — Niagara Falls from the Water Faucet? — The 'Killer Beam' of Academician Basov — The Laser and the Valve Face — The Duet with the Plasma

As the legend goes, the great Archimedes focused sunlight with huge mirrors and burned the invading Roman ships.

It is difficult to say with certainty what it is: a beautiful yarn spun by an ancient chronicler or a true story, because the science of history has no authentic documents that could confirm this interesting phase in the 'friendly relations' between Rome and Syracuse, one of the greatest cities of antiquity founded in Sicily by Corinthian settlers about 730 B.C.

But the idea of making a 'gun' that would concentrate sunrays into a powerful 'killer beam' has been attracting to many inventors since ancient times.

Among those who were the first in trying to harness sunlight for metal-making purposes was Henry Bessemer, the British inventor famed for his steel converter. On drifting away, with years, from 'big-time' metallurgy, Bessemer built, in 1868, a solar furnace to smelt copper and zinc. Unfortunately, the furnace turned out a technical failure; nor did the cloud-covered skies of Britain favour solar metallurgy. Because of this the new invention of Bessemer's went to the file of barren engineering ideas.

Late in the 19th century, some success in the melting of metals with sunlight concentrated by a parabolic mirror was scored by Professor V. Cesarsky in Moscow. The temperature at the focus of his concentrating reflector was as high as 3500°C. That was the 'right hell' in which to melt any metals, albeit in small quantities. But Cesarsky's experiments were not destined to pave the way for the Sun into metal-making.

Yet, the idea is basically sound. For the Sun, like a giant nuclear fusion reactor, is continuously generating and emitting energy in immense quantities. Although what our planet intercepts is only a negligible fraction—just one two-thousand-millionths of the total, but even this tiny bit reaching the Earth free of charge every year is thousands of times the total energy consumed the world over and is by an order of magnitude greater than all the energy reserves stored in fossil fuels. In fact, if all of the solar heat reaching the Earth's surface during only one second went down upon, say, the Sea of Azov, we would be able to go for a walk on its floor in a few minutes—all of its water would have been turned to steam by that time.

Unfortunately, man is wasting this wealth headlessly and uses only a few crumbs of the Sun's lavish gift in industry. Why is it that we aren't thrifty about it?

The main reason for this state of affairs is that solar energy is distributed over the Earth's surface far from uniformly, and so the solar energy per unit of surface area is low. Therefore, the basic thing for scientists and engineers to do is to devise ways and means of concentrating and storing solar energy.

That's why—recall Archimedes—specialists have always been turning to the mirror: it has been their hope in metal-making as well. Perhaps the first to harness the Sun for metal-making on a large scale was Professor Felix Tromb, a French scientist, and the event took place at Mont Louis in the eastern Pyrénées. Standing there fifteen hundred metres above sea level is a fortress built somewhere in the 17th century. In the early 1950s the fortress was destined to be 'rejuvenated': a team of scientists had chosen it as a site for a solar furnace designed under Tromb's guidance. Soon after the furnace was put in operation, a symposium was held at Mont Louis on the use of solar energy, and the participants had a chance to see the furnace in action.

"Very slowly, almost imperceptibly, a special platform was lifting a handful of white powder to the focus of a large parabolic mirror. When the platform was at the focus, the spectators could see a dazzingly bright, white flame go up in a flash.

"The white powder was zirconium oxide. Placed at the focus of the parabolic mirror, where the concentrated sun light raises the temperature to 3000°C, the powder melted. The accompanying flash could only be viewed through darkened glasses. The tiny heap of molten material lying on the platform looked like a volcano erupting in some distant geological era".

That's how a participant in the symposium at Mont Louis described the smelting of metallic zirconium by solar energy. The reflector consisting of more than five hundred mirrors was made to track the Sun automatically by an array of photocells. The sunlight reflected from the mirrors was beamed upon a large parabolic mirror which concentrated the solar energy in the crater of the furnace.

Several years after the event at Mont Louis, the Sun was made to work again at the mountain village of Odeillo, not far from Mont Louis. Another solar furnace was built there—a good deal bigger than its predecessor. Visitors to Odeillo are always struck by the sight looking not unlike the scenery for a science-fiction film. Standing next to the ancient spired church is a multi-storeyed building of an extremely functional design. This is the Solar Energy Laboratory. All of its north-looking facade is a giant parabolic mirror forty metres high and fifty-four metres wide. The slope opposite the building is studded with rows upon rows of heliostats—rather large mirrors. The sun rays caught by the heliostats are directed upon the parabolic mirror which reflects them as a powerful, concentrated beam onto a melting furnace, heating it to about 3800°C.

The Odeillo furnace can turn out close on two and a half tons of zirconium (as against the sixty kilograms produced by the furnace at Mont Louis). The thermal power generated by the sunbeam in the furnace is equivalent to a thousand kilowatts of electricity.

The most important thing about solar furnaces is that the molten metal doesn't pick up any objectionable impurities—they simply can't come from anywhere. Because of this, the metals and alloys made in a solar furnace are extremely pure and are in high demand. Solar smelting has some other advantages. Firstly, one needn't pay anything for the energy used—the generous Sun gives it to man free of charge and is prepared to do so for ever. Secondly, solar energy is not scarce as is the energy derived from petroleum or coal. As compared with nuclear energy, it isn't only absolutely safe to the environments during both generation and use, but doesn't leave any wastes which might, like radioactive wastes, cause a good deal of trouble because they would have to be disposed of in one way or another. This advantage of solar metallurgy is especially important in view of the ecological problems posed by many far from low-waste industries.

In the opinion of N.S. Lidorenko, Corresponding Member of the Soviet Academy of Sciences, who has been involved in the use of solar energy for many years, solar furnaces should preferably be used "to produce ultrapure metals and alloys, and the rare-earth metals scandium, yttrium and lanthanum which can be derived from their oxides only at a temperature of over 2000°C provided the energy source doesn't emit any pollutants".

At this writing, a major solar energy centre is being built in the Crimea so famed for its sunny weather—it will produce highly purified metals and other materials. Several metal-making solar furnaces have been in operation for some time already in Armenia, Uzbekistan, Turkmenia and other highly insolated regions of the Soviet Union. Pilot furnaces are being tried out to smelt high-alloy steel, and high-temperature alloys of titanium, tungsten, and molybdenum.

What the designers are mostly after is to increase the capacity of solar furnaces, and the crucial factor in the matter is the size of the concentrating reflector. However, the temperature in a solar furnace doesn't depend on the size of the reflector: it is solely decided by the accuracy with which the incident sun rays are concentrated, or focused. Theoretically, it would be possible to obtain at the focus of a melting unit a temperature of about six thousand degrees Centigrade—as high as at the Sun's surface. For this to happen, two things are important. Firstly, none of solar energy should be lost through absorption in the Earth's atmosphere. Secondly, sunlight should be ideally concentrated in the heliothermal plant. Since neither of the two requirements is satisfied, the actual temperature at the hottest point of a solar furnace is usually not over four thousand degrees Centigrade, but this is quite enough to tackle any task in metal-making.

Solar metallurgy has left its embryo stage. This is borne out by the following fact: the designs cited best by the jury at the 1983 competition organized by the USSR Union of Architects included a heliothermal complex for use in metallurgy. At this writing, the project is under construction: the site for the 'Sun' Complex has been chosen in the foothills of the Tian-Shan Mountains, not far from Tashkent, where the Sun shines more than three hundred days a year. As the project's authors envisage, the square in front of the building will be decorated with a symbolic sculptural group: Helios, the powerful god of the Sun, will be seen holding the reigns of a team of four horses pulling his fiery chariot.

While the sunbeam is only a novice in metal-making, the electron beam can justly pose as an experienced metallurgist.

Back in the past century scientists found that a sufficiently large potential difference between the surface of a solid and an external positive electrode would cause a stream of electrons to flow. By collecting them into a beam and speeding it up with a strong electric field, it is possible to build a powerful energy source called the electron gun.

We run into the electron beam every day: when we turn on our TV sets, we lift the barrier in front of a stream of electrons, and these set out to paint a picture on the screen. However, the electron beam in a TV set is not powerful enough. The beam produced by an industrial electron gun is tens or even hundreds of thousand of times more powerful. Indeed, it can melt the most refractory of metals. With it, electron bombardment can be used to advantage in many metal-making operations.

For the first time the electron beam was used to melt a metal by Sir William Crookes (1832-1919), primarily an experimentalist in chemistry and physics. He discovered the chemical element thallium in 1861, but soon his attention turned to the properties of highly rarefied gases and the rare earths. Perhaps the most important of his researches were *those concerned with electrical* discharges in rarefied gases. In 1879 he demonstrated an experiment in which the platinum anode of a cathode-ray tube was raised to a white heat and then melted as a result of bombardment in vacuum with electrons or, as Crookes himself believed, with 'cathode rays'.

In 1907, Marcello von Pirani, an American, used an electron beam in vacuum to produce uniform ingots of tantalum, an extremely refractory metal—it melts at around 3000°C. It was clear that the electron beam had a wealth of advantages to offer to metallurgy.

But advantages are one thing and their use on a commercial scale is something different. Before electron-beam melting could become a reality, one had to devise facilities which would produce electron beams, guide them, and provide a sufficiently high vacuum. All this came after World War II, that is, just several decades ago. Since then, electron-beam melting has taken a firm root among the processes by which crude ingots can be remelted or, more accurately, refined so as to yield extremely pure steels, alloys and metals. Such materials are indispensable in space technology, nuclear power, chemical processing, and many other industries. Conventional metal-making units cannot produce a metal entirely free from objectionable impurities. But this can be done when a crude metal is left at the mercy of the electron beam.

What is electron-beam refining like? A stream of electrons generated by one or several electron guns is brought upon an ingot of the crude metal to be refined. As the electrons strike the ingot, their electric energy is converted to heat—the metal is heated and finally melts. The rest is done by the high temperature and the high vacuum maintained in the electron-beam furnace. It is an easy matter for them to make short work of all gases and impurities present in the drops of molten metal. Emerging from this purgatory, the refined metal is collected in a bath of pure metal. As it solidifies in a water-cooled mould, the metal can either form an ingot or take the shape of a finished product.

Electron-beam refining brings down the oxygen, hydrogen and nitrogen content of the metal to a few tenths or even to a few hundredths of their percentage in the crude metal. In this respect the process is superior to any other refining processes. The metal tapped from an electron-beam furnace doesn't only carry a negligible amount of gases; it has a maximum attainable density and the best possible combination of mechanical properties.

Electron-beam refining offers some other advantages. For example, the process variables can conveniently be controlled over a wide range at will and, still more important, the process can handle practically any form of charge: electrodes, scrap, chips, just name them. On top of that, the process can produce large ingots tipping the scales at tens of tons—they are the right thing in the manufacture of rotors for heavy-duty steam turbines.

It may be noted that specialists don't see anything that might stand in the way of increasing the size and output of electron-beam furnaces. Indeed, the greater the furnace, the easier it is to focus the electron beam, and this has a wholesome effect on the run of the process. Mention should also be made of the fact that the electron-beam furnace can readily be used as the key link in the chain of a continuous metal-making process.

The field of application for the electron beam in metallurgy is expanding all the time. An incomplete list of the jobs it can do includes critical castings, extremely thin molecular films, the growth of single crystals from refractory metals, and zone refining. For all the bright records to date, the electron beam is yet to play its best part in metallurgy in the future, it appears.

Sun light has been illuminating the Earth for millenia—since the time our planet was born. Man came to know the electron beam only recently—in the past century. Yet, both may be looked upon as 'venerable elders' compared with the still young laser beam which flashed up brightly on the scientific horizon just a quarter of a century ago.

What is the laser? The name of the thing is an acronym—a word formed from the initial letters of a phrase: **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. The device emits light in the visible, infrared, or ultraviolet region of the spectrum in the form of a narrow and highly dense beam. It can be 'stimulated', or pumped, to emit its light with radiant, electric, chemical or some other forms of energy.

Is there a yardstick against which to compare the laser beam? Picture to yourself that some mighty creature has been able to channel the huge stream of water dumped every second by the Niagara Falls to pass in the same time span, that is, one second, through a water faucet. Ejected at a truly cosmic velocity, this jet of water would possess an unbelievably immense power! Of course, this analogy is overstretched—still, this 'tap water' model of the laser beam is useful.

The scientific principles that lie at the basis of the laser were discovered by Nikolai G. Basov and Alexander M. Prohorov in the Soviet Union and, independently, by Professor Charles Townes in the United States in the early 1950s. (The three were awarded the Noble Prize for their discovery in 1964.) Since the first laser using a single ruby crystal was built in the USA, the laser beam has been finding ever more uses in literally all fields of science and technology. Of course, it isn't of interest only to metallurgists. A great many science-fiction writers have more than once dreamt of a 'killer beam'. Now their dream has almost come true in the shape of the laser. Indeed, the laser is about to become a mighty weapon.

The laser has a focusing system which compresses its beam to an extremely fine stream measuring a split millimetre or even a few millionths of a millimetre across. This concentration of the beam very powerful by itself produces an unbelievably high energy concentration of up to ten watts raised to the twentieth power per square centimetre. How large is this number? If we were to obtain the same energy density from the Sun, all of its rays would have to be focused within an area the size of a circus arena.

Already the laser beam is doing well a good many metallurgical jobs: the casehardening of steel, the routing of sheet metal, and the surface impregnation of critical parts with alloying additions. It is worth while to dwell in more detail on alloying—an important metallurgical operation.

Making critical parts needs alloy steels—steels containing the expensive and scarce metals tungsten, cobalt, nickel and some others as alloying additions. In many machine parts, however, the bulk of the load is only resisted by the surface layer. Obviously, it would be enough to alloy it and to make the core of a part of an ordinary steel.

With the things as they stand in metal-making and mechanical engineering today, the whole of a part is made of the same material, say, a high-alloy steel. This means that a good proportion of the expensive metal is wasted. Add to this the metal lost as chips in machining or as gates and flash in casting, and you'll find that the cost of the part includes a good many items of no value to its service qualities. Again, it costs more to machine a part made of an alloy than of an ordinary steel.

Couldn't the laser help us cut all of these wastes? The answer is 'yes'. Take, for example, the valve such as is used in a car engine. In this part the bulk of the load is carried by its face — it has to stand up to far greater stresses and strains than the rest of it. It is just here that alloying can help the metal have the needed hardness and strength. Quite logically, it has been found that the valve can be cast of an ordinary steel and its face can then be surface-alloyed with the aid of the laser beam.

How does the laser beam tackle the task? The required amount of powdered alloying additions is applied to the surface of the part, and the laser beam is trained on it. The spot the beam strikes is raised to a very high temperature at once, the powder melts, and its ingredients find their way into the surface layer of the part. Guided automatically, the beam alloys the required area very quickly.

Laser alloying is highly beneficial economically above all because it saves expensive materials. But this process has more advantages to offer. For example, the alloyed layer has an excellent microstructure, and this goes a long way towards improving the properties of the metal. Also, the way that the alloying additions are distributed across the part's depth can readily be controlled by varying the power packed in the beam and the speed at which it traverses the part.

It is a sure bet that laser furnaces similar to their electron-beam counterparts will appear before long. At any rate, there are no technical obstacles for this to happen, and it may be hoped that the laser will be doing its bit in the manufacture of 'high-technology' materials in the near future. As scientists believe, special promise is held by the union of the laser beam and the plasma, another powerful carrier of energy. We will discuss it in the pages that follow.

The Hot Embrace of the Plasma

The Special Status — Everything in the World Is Relative — Down the Highway — Nothing of the Sort — The Plasma 'Steam Bath' — In the Arc Plasma Generator — 'Personae Non Grata' — The Thrifty 'Hostess' — By Joint Effort — What Happens in the Reactor — A New Lease of Life for Metals — Quick and Good — Twenty Years After

The plasma is often called the fourth state of matter. Why so? The point is that the other three — solid, liquid, and gaseous — have been known to man from time immemorial. The plasma (this is the state in which most of the Universe's matter exists — the stars, the nebulae, and interstellar matter) was discovered only recently: the word 'plasma' was coined by physicists in the 1920s, after the original definition by I. Langmuir. Well, 'last found — last ranked', so the plasma has to make do with its fourth place among the states of aggregation of matter known to science.

What is the plasma like?

When strongly heated, any material vaporizes—this ABC truth is known to us from school. But what happens when the vapour thus formed is heated more? The molecules of the vapour, or gas, break up into the constituent atoms, and these part with one or several electrons—in doing so, they turn into ions. There are other ways and means of ionizing a gas: through exposure to a strong electromagnetic radiation, an explosion or an electric discharge in a rarefied gas, its bombardment with charged particles, and so on. In an ionized gas, negative electrons coexist with positive ions. If both parties are present in equal numbers, such a gas is called a plasma.

The plasma markedly differs in properties from a neutral gas — this is why it is viewed as a separate state of matter. Among other things, it is highly responsive to the action of electric and magnetic fields which are rather indifferent to an unionized gas. As a rule, a plasma is heated to a very high temperature, so high, in fact, that physicists would call it 'cold' if it is heated to tens of thousands of degrees Centigrade. A plasma will be ranked as 'hot' only if its temperature runs into millions of degrees.

Let physicists deal with the high-temperature plasma on which great hopes are pinned by those who have to do with controlled nuclear fusion—a powerful source of energy yet to be harnessed. Metallurgists are interested in the low-temperature plasma because it can supply high temperatures—by a metal-maker's standards —unattainable in any other practical ways.

High-rate processes are a key to advances in metallurgy, and one way to raise the rate of a process is to conduct it at a high temperature. The electric arc suited metal-makers well for years: with it, far more heat could be obtained than in the open-hearth furnace or the converter. It seemed that, if necessary, the temperature could be raised still more by simply adding more amperes to the current and, hence, more watts to the arc. But nothing of the sort actually happened: the arc would just 'swell' and jump from the tip to the side of the electrodes, and the temperature in the furnace would refuse to go up.

Scientists devised another trick to keep the arc in check—they put a collar around it, and the arc was restrained from spreading sidewise. In the early laboratory units this collar was in the form of a water funnel which fitted tightly around the arc. So what happened? The temperature jumped at once to twenty thousand degrees. But this was no limit to the already high temperature: before long it was raised to fifty thousand degrees. At the same time, it was found that a highly ionized gas, or a plasma, was emerging from the funnel.

The metal-making skills of the plasma were noticed at once: it didn't only cope with the most refractory metals by turning them in a melt in literally no time; it provided an ideally sterile atmosphere in which the metal didn't pick up either carbon or oxygen. When it left the 'plasma bath', the metal was ideally clean, carrying no impurities whatsoever. The plasma had every reason to claim a critical post in metallurgy.

But it wasn't until the late 1950s and the early 1960s that the plasma left the laboratory to take up a job at metal-making works. It happened after a reliable device had been developed to produce the plasma and to keep it tame, known as the plasma generator. It enabled the Soviet Union, Japan, the United States, East and West Germanies, and some other countries to set out building plasma metallurgy.

The designs of the plasma generator are many and diverse. In the arc plasma generator most commonly used at metal-making plants the water funnel collaring the plasma stream has been replaced by a gas nozzle—a bottle-shaped copper anode enclosing a cylindrical cathode made of a tungsten alloy. When power is turned on, an arc strikes between anode and cathode. If now a stream of some gas, such as argon, is directed into the arc, the gas will be ionized. The 'bottleneck' compresses the arc and raises the current density there, and this sets the temperature of the gas rising along with its ionization—emerging from the nozzle is a strong plasma jet eager to fold the metal in its hot embrace.

Among the many jobs that metallurgists have given the plasma the key one is the production of high-quality alloy steels and alloys in a plasma arc furnace. The furnace is very plain in tastes: its feed may be any scrap. On leaving the furnace, it will be a pure metal which has got rid of practically all 'personae non grata', such as sulphur, phosphorus and carbon through the action of the plasma. That is, for example, how high-quality stainless steel extremely low in carbon is made. On the other hand, if the objective is a steel alloyed with, say, nitrogen, it will suffice to add some nitrogen to the plasma-generating argon rather than to use expensive nitrided ferroalloys. In this respect, the capabilities of the plasma process are very broad indeed: the plasma can be generated with practically any gas mixture of a composition adjusted to favour any desired chemical reaction in the furnace.

A happy trait about the plasma arc process is that the alloying additions tungsten, molybdenum, chromium, nickel or manganese, all of them expensive and scarce, aren't lost during the operation through burning—every gram of the addition passes from the charge into the finished metal.

Again, in contrast to the electric arc, the plasma arc is very thrifty about its heat: it loses very little by radiation which is a sort of mandatory 'ransom' in a good many thermal processes. This saving goes a long way towards improving the efficiency of the plasma arc furnace. Add to this the relatively simple design of the furnace, the wide range and ease of control over the rate of plasma flow, and its adaptability to automation, and you'll clearly see what kind of future lies with plasma metallurgy.

While the early plasma-arc pilot units could each hold a few tens or hundreds of kilograms, the furnaces currently in service at many metal-making works have a capacity of many tons. In 1973, a 10-ton furnace developed jointly by German and Soviet engineers who had accumulated a wealth of practical experience in the field was put in operation in Freithal, East Germany. The joint effort was carried on, and a 30-ton plasma arc furnace went to work at the same plant three years later. The range of high-quality steels the unit can make includes over a hundred grades for critical applications.

Apart from smelting a metal from an ordinary charge, plasma arc furnaces can refine metals and alloys. The objective of refining special-grade steels, precision and high-temperature alloys, and refractory metals and compounds is to improve their structure, to enhance their quality, and to add whatever elements they may need. Several designs of the plasma-arc refining furnace using a water-cooled mould have been developed at the Paton Institute of Electric Welding and the Baikov Institute of Metallurgy, USSR.

High-frequency plasma furnaces have been developed to grow single crystals and to produce ultra-purified materials. Instead of an arc plasma generator, the key piece here is an induction plasma generator: the plasma is produced through ionization with a high-frequency discharge and is heated by eddy currents. The plasma thus generated is a good deal purer that the one from an arc plasma unit.

The low-temperature plasma attracts metallurgists not just because it is a unique source of heat, but also because it is a readily adjustable chemical medium offering a solution to many metallurgical problems. Of unquestionable interest is one more direction in plasma metallurgy—the processing of ore materials (oxides, sulphides, and the like) through thermal dissociation in a plasma. When a charge of powdered ore is placed in the plasma jet inside a plasma reactor (as the piece of plant intended for the purpose is called), it vaporizes and turns into a gaseous mixture of atoms of the elements making up the charge. Now it remains only to enlist the services of various chemical agents (such as carbon, hydrogen and so on, depending on the composition of the ore), elevated temperature and magnetic fields in order to separate the 'right' atoms from the impurities, and to combine them into a compact metal.

The plasma reactor has already been able to extract from an ore the metal titanium for which the traditional metallurgical process involves quite a number of sophisticated operations. The plasma simplifies the task a lot as it readily breaks the union of titanium and oxygen. To do this, a jet of plasma generated from argon or some other suitable gas is brought upon a powdered charge of titanium oxide and magnesium. Acted upon by the plasma, the charge vaporizes, and the subsequent events take place in the vapour phase. In no time, the magnesium robs the titanium of its oxygen and forms a highly stable magnesium oxide. Left alone, the molten titanium accumulates on the bottom of the reactor and turns into an ingot.

With properly chosen process variables, the plasma reactor can produce not only pure metals from ores, but also refractory alloys and compounds, such as the carbides of zirconium, hafnium, and tantalum.

Of course, before ores can be processed with the plasma on a commercial scale, quite a number of obstacles—scientific, engineering, and economical—will have to be cleared. Research and development in this field is under way in many countries, including the Soviet Union.

As experts believe, the plasma can do a good many jobs in blast-furnace and steel-making plants using traditional technologies. In blast furnaces, the plasma might add a sizeable amount of heat, thus stepping up the production rate and cutting the requirements for the expensive coke. Plasma units have been designed which utilize the powdered wastes of steel making, accumulating in the furnace filters and usually going to dump. These wastes contain iron, zinc, nickel, chromium, molybdenum and other valuable elements which may be put to a better use than left lying in a spoil heap. Processed in the reactor of a plasma unit, the waste is again turned to a metal.

The plasma is sure to make a valuable contribution to powder metallurgy as well. Here, the starting material for the ultimate powder may be in the form of rods, wire, or coarse-grained powders. It is first melted by the plasma, the melt is sprayed, the sprayed liquid metal is allowed to fall through some distance, and the drops turn into round granules in the process. The exposure to the hot plasma lasts for a few microseconds, and the size of granules can readily be adjusted by varying the electric characteristics of the plasma, the flow of the plasma-generating gas, and the feed of the starting materials.

Now that we have learned a few things about what the plasma can do in metal-making, let's jump, say, two decades ahead and visit a plasma metallurgical plant of the future. Let it be located somewhere on the coast of the Okhotsk Sea. We can see the *Marine Mine*, a huge ship coming back from her mission during which she was dredging iron-manganese nodules covering the ocean's floor in thousands of millions of tons. Looking not unlike potatoes, the nodules are in effect an excellent polymetallic ore. They contain a high percentage of iron and manganese and, more important still, the valuable metals nickel, cobalt, and copper.

An underground pipeline conveys the oceanic ore from the waterfront directly to the charge bins of a plasma reactor shop. Here, the nodules are converted to ingots of metals so vital for industry.

The large 100-ton plasma arc furnaces in the next shop convert iron ingots and scrap to high-quality steel waited for at a nearby ship-building yard, a major steel user.

There is a plasma arc refining shop where ultra-pure metals of an especially high quality are produced, while a plasma spray unit turns out a wide range of powders from the iron and non-ferrous metals dredged from the ocean's floor and mined in Yakutia, Chukotka, and the Maritime Province.

Giant aerocarriages, jet-propelled dirigibles, magnetic-cushion trains, and sail-and-nuclear ingot carriers operated on schedule move the products of the plant we have built in our mind to many cities in the region, including the communities not yet existing on any map.

In Outer Space

Science Fiction Lags Behind Life — The 'Volcano' in Action — Straightening the Relations — You Must Spoil Before You Spin — Swan, Shrimp and Pike — Where Is Your Firewood from? — Near the Sea of Tranquility — The Mystery of Lunar Iron — As if Nothing Has Happened — The Key to the Problem — From the Catapult into the 'Dead Zone' — What's New on Mars? — The Captured Asteroid

It is not surprising when a science-fiction writer invents something far ahead of what exists in reality, be it science or technology. This is borne out by Jules Verne and his remarkable novels in which his heroes travel 'Twenty Thousand Leagues under the Sea' and fly 'From Earth to the Moon' well before all this is done in reality.

Yet, it sometimes happens that science fiction lags behind life. This is what G. Grechko, a Soviet cosmonaut, has to say on the subject: "Speaking of science fiction, I should note that it falls short sometimes of what space specialists would like to find in it. We are all close readers of science fiction. Not just because we want to compare our own experiences and knowledge with a free flight of imagination, but in an attempt to come upon new ideas. But this is where the otherwise daring science-fiction writers lag behind the real accomplishments of engineers. For example, unusual alloys have been produced in space, but none of the science-fiction books we have read carry a faint hint, let alone a description, of such processes".

For justice's sake, though, it should be said that a few hints can be found. True, not in science-fiction books, but in the writings of Konstantin E. Tsiolkovsky, a great visionary and a great realist. As one of the characters in his science-fiction novel, "Outside Earth", says: "Here (in outer space) we have a lavish opportunity to do whatever we like in the field of metallurgy".

Tsiolkovsky predicted that weightlessness could give vent to the physical effects that cannot manifest themselves on the Earth. In 1895, Tsiolkovsky published his "Dreams of Earth and the Sky and the Effects of Gravity" which saw the light of day in Moscow. One chapter bore the title: "A Description of Some Events Occurring in Zero Gravity". But outer space is not just zero gravity, or weightlessness. It also offers high vacuum and chemical sterility. Their happy union (unattainable on the Earth) can't but interest the scientists concerned with space exploration.

The first material processing and manufacturing experiments in space were carried out in 1969 by Soviet cosmonauts G. Shonin and V. Kubasov who flew *Soyuz-6*, an orbital station. It carried equipment with which they could weld metals, using the electron beam, the arc, and consumable electrodes. When they were preparing the experiment, the technologists faced a host of problems. Nobody knew if the usual heat sources could work in space. It was unclear how the metal would melt, spread and solidify in zero gravity. They could only guess how the molten metal would behave in an environment devoid of gravity, but exposed to the action of some other relatively weak factors, such as surface tension, adhesion, cohesion, and weak electromagnetic fields. Only an experiment could answer all of those questions.

After high vacuum was built in the orbital module of *Soyuz-6*, Kubasov turned on the *Volcano* welding unit, thus ushering in the era of space manufacturing. On the later missions, space manufacturing experiments were a mandatory item on the program. Quite a number of tests were made to see if other manufacturing and processing techniques could be used in space and if materials possessing unorthodox properties could be produced.

In 1975, shortly before the joint USSR-USA *Soyuz-Apollo* mission, A. Leonov and T. Stafford, chiefs of their respective crews, had a talk with a TASS news agency correspondent. Among other things, they touched upon metal melting and crystal growing in zero gravity. As Leonov said, "We plan to learn how zero gravity and vacuum can be used to prepare new materials, metals and semiconductors. As Soviet and American scientists believe, it is possible, in outer space, to make alloys from components which are immiscible on the Earth and to produce high-temperature materials." Stafford added that the astronauts flying *Skylab*, an US orbital station, had been able to grow single crystals of *indium antimonide*—the purest and strongest of all ever produced artificially.

The scientific program of the *Soyuz-Apollo* mission included one more metallurgical experiment. The point is that it is difficult, if possible at all, to make on the Earth an alloy of metals markedly differing in density: both during melting and solidification the heavier component would tend to sink to the bottom and the lighter component would tend to float up to the surface. Obviously, the result would be a segregated alloy which couldn't possibly be used for any practical purpose. The situation would be quite different in outer space. Zero gravity would equalize the heavier and the lighter components, and the alloy would be uniform both in composition and in structure. This task was assigned to a facility named the 'Universal Furnace': it was to make an alloy of light and relatively low-melting aluminium and heavy and extremely refractory tungsten.

Attempts to straighten the relations between materials hardly miscible on the Earth had been made in space earlier by the crew of *Skylab*, USA. They tried to alloy together gold and germanium; lead, zinc and antimony; lead, tin and indium. According to American specialists, the alloys were quite uniform. The same materials were used in similar experiments on the Earth, but the products differed a lot from their space counterparts. For one thing, the lead-zinc-antimony alloy produced on board *Skylab* had a higher threshold of superconductivity. The gold-germanium alloy made in space was capable of superconductivity, but its terrestrial counterpart wasn't.

Another experiment, called '*Sfera*', was made by Soviet cosmonauts B. Volynov and V. Zholobov on board *Salyut-5*, an orbital station, in 1976. Using a purpose-designed instrument, they watched the solidification of liquid metal in zero gravity. As the scientists who had devised the experiment believed, zero gravity would promote the formation of ideal metallic spheres out of the melt. The 'guinea pig' in the experiment was Wood's metal consisting of 50 parts of bismuth, 25 parts of lead, 12.5 parts of tin and 12.5 parts of cadmium.

But, as the saying goes, you must spoil before you spin: on solidifying, the droplets of molten metal tended to turn into tiny 'pears', 'onions' and other similar shapes, but not regular spheres. Despite the failure, the experiments will be followed up. If they prove successful, they will open up tempting prospects before metallurgists: in order to make a blank for a ball bearing on the Earth, you have to carry out over a dozen different operations, losing a lot of metal as waste in the process. Again, the structure of the balls thus made leaves much to be desired. Because of this, we wish to believe that experiments along the *Sfera* lines will in the long run prove a success. Then, a ball-casting factory will go into operation in orbit around the Earth.

More manufacturing experiments were made by Soviet cosmonauts on board *Salyut-6* and *Salyut-7*. Using the '*Splav*', '*Kristall*' and '*Isparitel*' facilities, they produced quite a number of alloys and semiconductor materials of importance to science. Of special interest was the growing of a ternary cadmium-mercury-tellurium (or CMT) single crystal in weightlessness.

A CMT crystal is a solid solution of cadmium and mercury tellurides. This semiconductor material is indispensable in infrared imaging devices used in medicine, geology, astronomy, radio engineering and many other important divisions of science and technology. The material can hardly be obtained on the Earth because its components behave in much the same ways as Swan, Shrimp and Pike in a fable by Ivan Krylov: instead of a uniform alloy, they produce a sandwich. In order to obtain a tiny CMT chip, one has to grow a large crystal and to cut out of it an extremely thin wafer—the rest has to be discarded. But it can't be otherwise: the CMT chip must be pure and uniform to a few hundred-millionths of a percent. It is no surprise that these chips carry a high price on the world market.

This explains why metal scientists pin so much hope on materials manufacturing in microgravity: with no gravity to act upon them, the constituent elements have no reason to compete for a particular part of the crystal's volume. Space manufacturing experiments have been encouraging: the specimens carried back to the Earth have been found to be sufficiently uniform in composition and to have a regular structure. There is every ground for believing that the time is not far off when the remarkable crystals grown in the expanse of outer space will toil in many instruments.

We have deliberately dwelled at length on space manufacturing experiments. What are experiments today will be commercial space processes and plants tomorrow. The many tests made by Soviet cosmonauts and American astronauts have shown what bright prospects are opening before the manufacture of various metals and alloys in space.

However, the use of the unique conditions existing in outer space for manufacturing purposes is only one side of the coin. The other is—and no less important—the exploitation of material resources existing in the cosmos. Many scientists believe that, as the Earth's crust is depleted more and more of its mineral deposits, the need will finally arise to tap the mineral wealth of space. In the words of Academician Sergei P. Korolev, "Man sometimes looks like a person who burns the walls of his house in order to warm up himself instead of going to the woods and cutting firewood there". Of course, every ton of iron, zirconium or tungsten ore mined on, say, the Moon and hauled to the Earth would cost a lot of money—that has to be admitted frankly. But the first ton of iron ore produced in a new mine on the Earth costs much as well, while the thousandth ton and, the more so, the millionth ton costs far less. This trend would also hold for the ores mined in space. Again, who says that the ore mined on the Moon must be carried to the Earth? Wouldn't it be possible to smelt metals right there?

Back in 1963, E. Iodko, a Soviet scientist, came up with an unorthodox process for extracting lunar iron. According to him, iron smelting on the Moon should be replaced with iron sublimation—the direct conversion of a solid to its vapour. On passing through a shaft packed with lumps of a carbonizing material, the iron vapour would turn into a mixture of iron, carbon and carbon monoxide—all in the gaseous state. In a condenser, the iron and carbon would come in contact with the cold surface of an endless conveyer, turn into a solid state, and lodge on the conveyer while the carbon monoxide would escape to the lunar 'atmosphere'. It would be possible to adjust the carbon content at will and to produce various grades of steel by varying the temperature in the shaft.

As the project's originator wrote, "Manufactured in the extremely high vacuum that exists on the Moon and the other cosmic bodies, the steels and alloys would be truly 'unearthly' in their strength, ductility and other properties, entirely free from occluded gases and nonmetallic inclusions. Indeed, the conditions that are unfavourable for metal-making exist on the Earth with its dense and oxygen-saturated atmosphere, and not on the Moon. Devoid of any atmosphere, the Moon and the other heavenly bodies wouldn't just meet astronauts' needs for ordinary and high-quality metals; they would supply the Earth and the other planets with metal products".

An entirely different idea lies at the basis of a pilot unit for the extraction of iron from lunar rock, developed by American specialists. Its parabolic mirrors would concentrate sun light to melt lunar rock, and the melt would then be electrolysed, using the energy of solar batteries. In this way, the metal would be separated from the barren rock. It has been calculated that this type of unit the size of a writing desk (in company with solar panels covering an area equal in size to a football field, though) would be able to produce about a ton of iron every day.

Iron isn't alone in attracting scientists concerned with the development of outer space. Another metal of importance is titanium. It had been predicted well before the US *Apollo* spacecraft and the Soviet *Luna* probes carried back to the Earth samples of lunar rock that the lunar ground should contain a fairly large percentage of titanium oxide. What was a hypothesis yesterday has now been verified by experiment. Who knows? It may so happen that at the turn of this century newspapers will carry reports that the Moon's first titanium mine has gone into operation somewhere near the Sea of Tranquility or the Ocean of Storms.

Pure metals are a rare occurrence on the Moon as they are on the Earth. Nevertheless, tiny specks of pure iron, aluminium, nickel, and zinc have been found there. On the Earth, they can't be found in native state at all.

When in 1970 *Luna-16*, a Soviet automatic lunar probe, carried back to the Earth samples of regolite, the Moon's topsoil, many of the Soviet Academy's institutes set out to analyse the precious specks of the lunar material as carefully as they could. Before long regolite proved it was worth while studying. Much to the scientists' surprise, the samples included tiny particles of pure iron entirely free from the minutest traces of oxidation. It was a great surprise, indeed, for on the Earth iron rusts everywhere to the dismay of mechanical engineers and builders. But the most surprising thing was that the lunar iron wasn't in a hurry to be oxidized on the Earth, either. Days, weeks, and months passed, but the iron brought from outer space retained its juvenile purity.

Several years have passed since then, but rust has failed to attack the mysterious iron. Nor has oxygen been able to attack the iron specimens collected on the Moon by *Luna-20*, *Luna-24*, and the *Apollo* spacecraft. Why is it that lunar iron is so resistant towards corrosion?

Hundreds of pains-taking experiments were made before the question could be answered. Laboratories were set up on the Earth in which the conditions were close to those existing on the Moon, and sophisticated instruments 'probed' the specks from outer space. The experimentors were greatly helped by X-ray electron spectroscopy, a new analytical tool. With it, detailed information can be gleaned about the interaction of atoms in the surface layer of a material just a few hundredths or even thousandths of a micron thick.

The mystery of lunar iron has now been unravelled: it owes its extremely high corrosion resistance which is many times that of the steels and alloys manufactured on the Earth to the solar wind—the supersonic flow of gas composed of protons and electrons which is continuously blowing from the Sun through the solar system. As they bombard the Moon unprotected by any atmosphere, protons 'snatch' oxygen off the lunar surface and carry it into the expanse of the Universe. Rid of its oxygen, the iron becomes so highly 'immune' that no oxidation can occur either on the Moon or on the Earth where it firmly beats off all attacks of corrosion.

The unravelled mystery of lunar iron has let physicists and metallurgists use the discovery in their 'vested' interests. The idea is to bombard metal parts with ions so that an armour of extremely tiny particles is produced on the surface, resistant to oxidation. An interesting experiment was made in one laboratory: the word 'Moon' was written on a stainless steel disc, the inscription was bombarded with a beam of ions, and the disc was then placed in the vapour of aqua regia—a mixture of three parts hydrochloric acid and one part nitric acid. So what happened? A quarter of an hour later, the disc was covered with a coat of rust everywhere except the word 'Moon' which gave off metallic lustre as if nothing had happened.

It is for some time now that man has been regarding outer space as his future home. Numerous plans have been advanced for huge orbital stations, and many space cities have been built on the pages of science-fiction books. Indeed, there is even a theory of space colonies, advanced by Tsiolkovsky. It is interesting to note that he proposed to use the materials of planets and asteroids for the colonies. This view is shared by the originators of many similar projects.

An interesting idea has been advanced by a team of American scientists headed by Professor O'Neal. As they believe, space colonies might well be built with existing technology. The new techniques that may appear lie within the limits of today's knowledge. In their opinion, extra-terrestrial space is an energy- and substance-rich medium rather than an emptiness. Outer space is abundant in solar energy, which is easy to use. The Moon and the asteroid belt could supply the necessary materials.

O'Neal has compiled a detailed balance sheet of the space project, complete with a bill of materials indicating where the colonists would be able to get whatever they might need and in what quantities. Even water wouldn't be carried from the Earth. Instead, liquid hydrogen would be transported to outer space, and the oxygen required to produce water could be obtained on the Moon. The key building materials, above all aluminium and titanium, could be produced there too. He even envisages moon-rovers to carry ore and catapults to send raw materials from the Moon to metal-making plants that should, as the scientist thinks, be built in the "dead zones" between the Earth and the Moon where the latter's pull of gravity is balanced out by that of the Earth's.

Because of its proximity to the Earth, the Moon figures in most plans for the mining of minerals in outer space and the extraction of metals from them. In contrast to them, Herbert George Wells, the famous British novelist and science-fiction writer, turns in his "The War of the Worlds" to Mars. In it, an agile machine, working from sunset to the emergence of the stars, is able to make at least a hundred bars of aluminium directly from clay.

Some futurologists think it would be worth while using the minor planets, or asteroids, which consist largely of iron and nickel. Many thousands of them are revolving around the Sun, mainly between the orbits of Mars and Jupiter. Sometimes they come quite closely to the Earth. As scientists believe, such an asteroid could be towed by powerful rockets into an orbit near the Earth and then worked for its iron and nickel.

There is a plan by which automatic probes would be sent to an asteroid in order to smelt its material with the aid of solar furnaces into huge ingots weighing millions of tons. Rockets would tow the ingots to an orbit close to the Earth, and it would then remain only to bring them safely to the Earth's surface. But how? Some think this could be done by melting the ingots in orbit and injecting a gas into the melt. The blocks of expanded material thus produced would then be easy to manoeuvre to a safe 'splash-down' in the ocean, where they would be floating until ships tow them to metal-making works on the shore. It has been calculated that, at the existing rates of consumption, one cubic kilometre of asteroid material would be able to yield 15 years' supply of iron and more than a thousand years' supply of nickel for the Earth.

Those are daring plans, aren't they? But was it long ago that many prominent scientists were sure that man's landing on the Moon was just another daring plan?

At the Threshold of the Third Millenium

The Journey in the Milky Way — Where Is the Silhouette? — The Sparkling Sail — Off the Coast of South America — In Partnership with the Nuclear Jinnee — Miles and Miles Away — Benefits Are There — The Volcanos Aren't Asleep — From Vesuvius' Lava — Is There a Recipe? — Magma Flows into the Reactor — At the Bottom of the Red Sea — The Alchemy of the 21st Century

Almost proverbially, to dream is human. In his dreams man has tried many things. One is transport. Obeying the imagination of bold visionaries, we see our descendants on a journey in the Milky Way on board rocket ships nearly as fast as light itself, or on a week-end cruise around Europe, Asia and Africa on board underwater oceanic linears.

In this sense metallurgy has been unlucky. Metal-making is a down-to-earth occupation which doesn't suggest any future scenes. It is small wonder, therefore, that science-fiction writers have paid so little attention to it.

Unless you have a 'time machine', it isn't at all easy to see what the future has in store for metallurgy. Yet, let's try and sketch, perhaps a bit timidly, what metallurgy will be like in the third millenium. Let's take it in at a glance. What can we see?

The skyline of iron-and-steel plants no longer shows the silhouettes of blast furnaces, and the blunt-nosed cigars of hot-blast stoves, their loyal 'air-bearers' are nowhere to be seen. They served man faithfully for centuries, but now the day has arrived for them to come off the stage, giving way to their 'no-coke' successors—units for the direct reduction of iron ore. The bristle of the tall stacks of open-hearth furnaces has been shaved off the skyline as if with a giant razor blade: good memory of the open-hearth furnace is still kept in museums, but the steel-making art is now dominated by the converter and the electric furnace.

A short distance away we can see an unusual structure looking not unlike a giant sail. The Sun has emerged from behind the clouds, and the sail is sparkling like a huge diamond: it is a multi-tier solar-light concentrator which sends a highly concentrated sunbeam onto the melting zone of a solar furnace.

Spread over a huge pond connected by an underground canal to the sea is a dense cobweb of pipes—hundreds of sorption units extract gold, uranium, molybdenum and other valuable metals from sea water.

What we can see can't give a complete picture of metallurgy in the 21st century: many plants, shops and mines will then be operating in outer space, under the ground, and in oceanic depths. For example, Dar Veter ("the Gift of Wind"), a leading character in the *Andromeda Nebula*, a science-fiction novel by I. A. Yefremov, a Soviet scientist and author, is working at an underwater titanium mine off the coast of South America. This is what he sees when he comes there to work: "Jutting far out into the ocean was a man-made bank terminating in a wave-washed tower. It stood at the edge of the shelf falling steeply into the ocean to a depth of a kilometre. A heavy walled concrete shaft strong enough to stand up to the deep-water pressure ran vertically down beneath the tower. At the bottom the shaft entered the top of an underground mountain which consisted of nearly pure rutile, titanium oxide. Everything necessary to work the ore was done there, under the water and in the mountains. Only large ingots of pure titanium were lifted to the surface, leaving clouds of slime far around them".

Nuclear power is bound to give metallurgy a good many new things. Already now engineers are busy looking for ties which would unite the might of the nuclear jinnee and the energy-avid manufacture of metals.

By the start of the next millenium, yearly steel output the world over will probably be one and a half or two thousand million tons—this will be twice or even three times the figure today. This will entail a proportionate increase in energy consumption by metal-making.

Coal and natural gas, the most commonly used energy sources today, won't be able to cope with the task. Nor has Nature seen to it that coal fields and gas deposits should always lie close to iron ore. As often as not, train-loads of coal have to be hauled from miles and miles away or gas pipelines thousands of kilometres long have to be installed to carry the fuel to the ore deposits where iron works are usually built. Or train-loads of ore are shipped to coal-rich regions.

The picture is altogether different with the nuclear fission reactor. For one thing, it can supply practically any quantity of energy for a plant or a group of major plants. For another, it may be built at any place meeting process and economic requirements. This explains why metallurgists rely increasingly more often on the nuclear reactor in their plans for the future.

Of course, what makes the nuclear reactor especially attractive is its principal product—the energy released from the atomic nucleus. Yet, its by-product, the coolant gas, may likewise be used to advantage in metal making: its heat can be recovered for utilization in, say, blast furnaces or direct reduction units. True, the coolant gas leaving a reactor is rather cool by metallurgists' standards—just several hundred degrees Centigrade. But nothing stands in the way of raising it to a temperature that is needed for metal making. This can be done quite easily by the plasma jet or the laser beam (the usual methods of heating might be used as well, though). The benefits are obvious— it is easier to do than to start from scratch.

This is a minimal program for nuclear metallurgy. In their long-term plans, scientists and designers pin their hopes on the electricity generated by a nuclear fission power plant supplying a huge iron and steel works. They are mostly attracted by the economic benefits they stand to have, such as lower capital outlays for construction, improved productivity, reduced cost of steel, and so on. But there is something in it for the environment as well. We may imagine all of the nuclear-power metallurgy going underground, thus leaving a cleaner skyline.

Nuclear-power metallurgy is being taken seriously in many countries. Japan, for example, has set up a special committee which is to look into the possibility of using nuclear power in metal-making. Several West European countries have joined their efforts in the European Club for Nuclear Ferrous Metallurgy. Many big companies in the United States have also found it advisable to coordinate their activities in this field. Of course, the issue hasn't been overlooked in the Soviet Union, either, with the Bardin Central Research Institute of Ferrous Metallurgy leading the field. In short, the time isn't far off when cheap but excellent steel made with the aid of nuclear energy will hit the world market.

What else may change in the manufacture of metals? In all probability, the electron beam will soon acquire new metal-making jobs, the laser beam will change its 'amateur' status to become a 'pro', and the plasma will move to the foreground. There is everything for metallurgists to hope that they will be able to find many metal-making uses for ultrasound, the electromagnetic field and the high-frequency current—each has been helpful in metal-making for a long time already.

Of course, some other approaches, seemingly unorthodox but quite feasible nonetheless, will appear in the manufacture of metals, too. For example, we may well imagine the extraction of metals from volcanos. It is no mere chance that volcanos are sometimes looked upon as Nature's metal-making plants: the chemical reactions that take place inside them aren't unlike those occurring in blast furnaces, steel furnaces, copper smelteries, and so on. When he happens to see the white-hot stream of lava leaving a volcano, any metallurgist feels at home, I'm sure.

The volcanic activity inside the Earth has been behind the formation of many mineral deposits. The accumulations of mercury, silver, gold, iron, copper, nickel, manganese and other valuable elements are now found at the scene of what once was a violent volcanic 'life'.

A team of scientists at the Far Eastern Division of the USSR Research Institute of Mineral Resources have compiled a paleovolcanological map of the Soviet Far East. What is this unusual map like?

About two thousand volcanos were active in the region many million years ago. Gradually, they went dead, some of them leaving behind no 'mementos' by which to remember them. Some have sunk flush with the surface, others have gone underground (one such volcano is the site occupied by the city of Khabarovsk now). The new map showing all of the extinct volcanos of the Soviet Far East is above all intended for geologists. It can be a reliable guide in their search for minerals, especially at the boundary between the land and the ocean where the belt of both active and extinct volcanos is located.

Since we are more concerned with metals than with geology, let's leave the remains of the prehistoric volcanos and turn to the fire-breathing lava of those still alive and 'kicking'. From a metallurgist's point of view, volcanic lava raised to an extremely high temperature is an admirable feedstock for the production of iron, aluminium, titanium, magnesium, calcium and many other metals. Just recall Italy which was, during World War II, extracting her aluminium from Vesuvius' cold lava for lack of other sources.

Of course, the solid, cold lava is much safer to handle than the white-hot flow escaping from the infernal crater. But a question suggests itself: Isn't it possible to tame this flow of the ready-made furnace charge prepared and melted by the Earth itself? Not to let the lava solidify and to work it while it's hot would save a huge amount of thermal energy. How should one go about it?

Hardly any one would be able to give a recipe today, but the search for answers to some problems that might bear upon the future of volcanic metallurgy is under way. It is a quarter of a century now that the Institute of Volcanology set up in the Kamchatka Peninsula, a land of volcanos and geysers, has been handling the matters in earnest. It has no department of metallurgy, but research into the chemistry of the Earth's inside is in full swing there.

Volcanologists the world over are learning how to predict eruptions with precision. When they are able to do this, man will be the true master of the dreadful element.

An attempt to put a straight jacket on a volcano was made in 1983 when the violent Etna in Sicily showed its temper for the umpteenth time. To save the villages, the tourists' camps, the gardens, the vineyards, the forests and the crops on the slopes of and at the foot of the volcano, Italian volcanologists and shot-firers tried to steer the magma stream down an artifical bed dug by precisely calculated explosions. Not that they were able to achieve the goal they had set, but what they did inspires the hope of an eventual success.

Let's be optimists and picture to ourselves a scene like this: The tamed lava is timidly flowing down the slope of a volcano towards an unusual structure. This is a transportable plasma reactor moved over from the previous site the day before. (It may be noted that the chemical reactions proceed in a plasma at a very high rate, and the reactor can therefore be made rather small. For example, a reactor for the plasma pyrolysis of methane with an output of 25 thousand tons of the gas a year is no bigger than a rolled sheet of a drawing. As is seen, the piece of plant we need may be not only transportable, but even portable.) The reactor draws its power from a geothermal power plant—it converts the energy of the hot steam leaving the volcano into electricity. It may be added that quite a number of geothermal electric power plants are already in use in many countries, including the Soviet Union.

We won't go into a detailed discussion of the physical and chemical events that may take place in a plasma reactor: the capabilities of the plasma, especially in partnership with chemistry, are unlimited, indeed. Therefore, you needn't overstretch your imagination in order to picture to yourself how the magma charged into the reactor can be converted into ingots of the metals it carries, and other useful products.

When will the Earth's first volcanic metal works go into operation? Where will this happen: at the foot of Fujiyama, in the Kuril Islands, or in Hawaii? Perhaps, the answers will be given by the 21st century. But its predecessor is well able to cope with another task also related to the ore-forming activity of volcanos.

The point is that the hot waters rising to the surface in regions of high volcanic activity carry sizeable amounts of dissolved metals. It has been calculated, for example, that Ebeko, a volcano on Paramushir, one of the Kuril Islands, delivers along with thermal waters close on 700 tons of minerals, including thirty tons of aluminium and sixteen tons of iron. Off the Easter Island, volcanic waters dumping iron compounds onto the oceanic floor have built up huge iron deposits there. The area of the ocean's floor taken up by liquid iron ore mixed with vanadium, manganese and molybdenum is only slightly smaller than France or Spain in size. For the time being, all this wealth is in Poseidon's hands, but even today it is technically feasible for man to transfer all of these 'deposits' to his account.

Volcanism is also responsible for what has been observed by the French scientists working in the Red Sea. They ran, off the Sudan coast, into a huge depression some two kilometres deep, filled with very hot water. The explorers went there in a deep-water submersible, but had to come back to the surface because the steel hull of the vessel was heated to more than forty degrees Centigrade. The water samples they collected showed that the depression is filled with a hot liquid ore unusually high in chromium, iron, gold, manganese and many metals.

Soon other depressions were found in the Red Sea, also filled with semiliquid ores high in zinc, copper, and silver. These seabed mines have attracted businessmen in Saudi Arabia and the Sudan who are planning a joint venture which will be in charge of the mining operations in the Red Sea. They have invited a West German firm which has undertaken to develop the necessary process and plant. A purpose-designed ship is being built to carry a pipe extending as far as the seabed, made up of many sections as in drilling oil wells. The far end of the pipe is to have a suction nozzle which will be buried in the ore bed. The jets of sea water expelled by the nozzle will loosen up the ore, and the slurry will then be pumped aboard the ship. Since it would be uneconomical to carry the slurry ashore for further processing, it will be beneficiated right on board the ship.

It hasn't yet been decided how to protect the Red Sea from pollution with ore-dressing wastes which are likely to run into hundreds of tons a day. In one environmental control scheme the wastes are to be dumped by a pipe to a depth of four hundred metres, that is, below the boundary of the biologically active zone in the Red Sea.

Thus, we've visited several metal works of the future on the Moon, under the ground, at the base of a volcano, and on the seabed. What else has the coming century in store for us? What metal-making technologies will highlight the metallurgy of the 21st century?

An interesting idea about the future of high-quality metal-making was advanced in his day by Ivan Bardin. In his paper for a book, "Reports from the 21st Century", he said: "I think that man can 'build' the alloy steels he may need by exposing them to radioactivity rather than by alloying them with rare and expensive elements—he can build up the steel of any desired analysis right in the ladle from atoms of iron, carbon and, maybe, sulphur and phosphorus or, perhaps, some other abundant element suitable for the purpose, all added to the melt. The job could be done as follows. There would be a moving ladle filled full with molten metal. It would stop for a few seconds at a machine looking not unlike the cobalt gun used to treat malignant tumors. The pear-shaped lead vessel enclosing a suitable radioisotopic source would bend over the ladle to bombard it with radioactive particles and to bring about the necessary nuclear transformations in the melt. A few minutes later the steel would be poured into moulds—it would have changed its analysis by that time. Further changes would keep taking place for some days more in the already solidified steel, due to its own radioactivity induced by irradiation. Probably, the same technique—nuclear transformations brought about by irradiation—could be used to produce the rare and trace metals. It isn't at all unlikely that a whole industry, radiation metallurgy, will emerge, transforming the more abundant elements into the scarce ones. Despite the rapid progress of technology, however, radiation metallurgy will hardly become a full-fledged industry even by the start of the 21st century. This is a matter of a more distant future".

Iron on Its Way out?

(In Lieu of an Epilogue)

Different View-Points — At the Brussels World Exhibition — Alloys with Memory — Glassy Metals — Whiskers Come in Vogue — Why Are Composites So Special? — Following the Computer's Recipe — Purity Leads to a Success — The Vigilant Rivals — Despite the 'Pension' Age

From the view-point of historians and archaeologists, the Iron Age (as a phase in the primeval and early history of mankind) saw its last days somewhere around the beginning of the Christian era. But even today, twenty centuries later, iron remains the basis of material culture. Therefore, if we look at things from the view-point of builders or machine designers, the Iron Age is still having its hayday, and there is no end for it in the offing. Man hasn't yet come to know any other material that could compete with iron or, more accurately its alloy, steel, in strength, reliability, workability, availability, and low cost.

Iron is everywhere to see: it is in high-rise buildings and beautiful bridges, in the swarms of cars scuttling on the planet's roads and the tall needles of TV towers piercing the sky, the dense cobweb of railways covering the face of the Earth and the uncountable numbers of metal-cutting tools, transformers, and pipelines. Nothing could have been built without iron. According to A. I. Tselikov, man has produced in this century ten times the amount of iron he made in all of the preceding centuries. Isn't this a proof that iron hasn't become obsolete? Rather, it keeps on gaining ever more ground in a wide range of man's activities. It is no mere chance that the World Exhibition held in Brussels in 1958 had as its symbol the Atomium, an unusual structure towering high above all the other buildings. Even today, its nine huge metallic spheres, each eighteen metres in diameter, appear to be hovering in the air: eight at the corners of a cube, and one at the centre. The Atomium is a model of iron's crystal lattice enlarged 165 thousand million times. It symbolises the greatness of iron, the workhorse of a metal, the master metal of industry.

Yet, however important the role of iron may be nowadays, however wide the range of products made of it is, technology today needs other materials as well. For the 20th century, unlike any of its predecessors, is a time of high speeds, high process temperatures, and tremendous structural loads. And this means that the requirements to be met by the materials are becoming ever more stringent. This explains why the last decades have seen the emergence of a host of new materials, both metals and nonmetals, many of them possessing unbelievable properties.

As an executive in Arthur Haily's *Wheels* says in a talk with newsmen, new things will undoubtedly find their into everyday life, and the newest of them will all be bound with materials. As an example, he mentions the honeycomb structure—stronger, more flexible, and lighter than steel. He also talks of a metal which will be able to remember its original shape. Should a car owner bend a wing or a door of his car, the damage can readily be rectified by giving the part a heat treatment.

Two or three decades ago an idea like this would have been treated as a sheer fantasy. Today, metals with memory are well known to scientists and machine designers. What has happened in the meantime?

In the mid-1960s, an alloy of 55 percent nickel and 45 percent titanium, named Nitinol, was patented in the United States. Rather light, strong, and highly resistant to corrosion, the alloy ranked as a good material of construction—not more. As its originators kept on experimenting with the alloy, they ran into something quite unusual—the metal was found to have memory. During one of the many experiments, a Nitinol filament was coiled into a helix, worked in some way, heated to 150°C, and allowed to cool. Then a load was suspended from it, stretching it straight. When the straight wire was again heated (to about 100°C), it coiled back into a helix before the eyes of the surprised researchers.

More experiments followed, and ever more complicated shapes were tried, but the metal would imperturbably take on its original shape. Once the filament was shaped into the word 'Nitinol', then heated, cooled, and deformed beyond recognition. But when a strong pulse of electric current was passed through the misshaped knot and heated it, the experimentors could see the filament form the word 'Nitinol' again.

Machine designers have found a good many uses for the alloy where its remarkable abilities can be utilized to the utmost. Among other things, Nitinol has been recognized as the material of choice for rivets to be used in places accessible from one side only. The metal is treated so that it 'remembers' the shape of a complete rivet, one of the heads is temporarily worked back to a round rod, and the one-headed rivet is set in its designated hole. Now it is enough to heat the rivet a little, and it will 'recall' the shape of its head at the opposite end. Such rivets are easy to set and work well.

Nitinol has been used as the material of construction for the antennas carried by Earth satellites. Coiled in a tight ball, an antenna can conveniently be stowed away in a small compartment at shoot-off. In space, heated by sun light, the ball uncoils, and the antenna stretches out its arms. The same principle can be used to build a radio telescope with an antenna over a kilometre in diameter. Some designers are even playing with the idea of a thermomechanical heart pump: it could use a Nitinol filament which would alternately contract and expand much as the heart muscle does.

Nitinol isn't alone. A wide range of binary (two-component) and ternary (three-component) alloys similar to Nitinol in behaviour have been developed to date, such as titanium-cobalt, titanium-iron, zirconium-rubidium, and copper-aluminium-nickel.

As we know from school, all metals and most of the other solids have a crystalline structure in which the atoms or molecules are arranged in a regularly repeating pattern called the lattice. The situation is entirely different with gases and liquids. One example is ordinary water. What is it like? A haphazard accumulation of H_2O molecules. Once, however, water is cooled to below zero, its freezing molecules take up positions in an orderly rather than random fashion and there appears a regular structure—the crystal lattice of ice. That is how a plain rain drop turns into a beautiful snow flake. This overhaul leads to a marked change not only in the appearance, but in many physical and chemical properties of the substances as well.

This doesn't mean that all solids are crystalline in structure. One example is glass: it remains amorphous both when solid and liquid. Isn't it possible to arrange things so that an amorphous metal melt will remain amorphous in the solid state? This would produce metallic 'glasses' or 'glassy' metals. This isn't just an idle curiosity: metals with glassy properties can surely possess some unusual properties. How one should go about it?

As a rule, it takes a fairly long span of time for a substance to crystallize from its molten or simply liquid state, so there is enough time for the atoms (or molecules) to form a highly ordered lattice. Nothing of the kind would happen if the melt or liquid is cooled faster than its atoms can crystallize.

The people who were the first to experiment with metallic glasses turned to high vacuum and cryogenic (that is, extremely low) temperatures for assistance in raising the cooling rate to a million degrees per second. As many experiments have shown, if we apply the vapour of a metal onto a metal plate placed in a chamber where the conditions are as we've just described, a 'glassy' ribbon will form on the plate at once.

The first metal to go 'glassy' has been bismuth. It has been found that the paper-thin ribbon of 'glassy' bismuth is far more easily magnetized and far more electrically conductive than bismuth is in its normal state. Even at room temperature the resistance of a glassy bismuth ribbon to electric current is a fraction of what it is in the crystalline state.

Today, the range of metallic glasses is fairly wide: it includes steel and quite a number of refractory metals. Nor is it necessary to resort to high vacuum and cryogenic temperatures any longer. Now liquid metals can be quenched against water-cooled, heat-conducting wheels spinning at a high speed to produce metallic glasses. The melt cools in a matter of a few thousandths of a second, and the continuous ribbon is wound on a take-up spool.

Metallic glasses today are a 'hot' item in the field of high technology. All kinds of experiments are being made with them all over the Earth. And not only on the Earth: in 1984 experiments involving the manufacture of metallic glasses were made in space during the stay of a Soviet-Indian visiting crew on board *Salyut-7*.

The experiments used the *Isparitel* facility designed by the Paton Institute of Electric Welding, USSR, additionally fitted with a unit which enclosed the main 'characters' of the action: tiny balls of a silver-germanium alloy prepared by a metallurgical laboratory in the Indian city of Hyderabad. Inside the unit, the balls were supported by ingenious metal loops so that they couldn't touch the walls of the crucible in which they were to be melted by an electron beam.

Since the *Isparitel* facility was located in an air-lock and exposed to space vacuum, the molten metal was bound to cool instantaneously and turn to a 'glass'. Watch on the process temperature was kept by highly sensitive thermocouples which were able to register supercooling with a jeweler's precision.

The specimens of the 'glassy' alloy, highly valuable to metal scientists, were carried back to the Earth for an all-round scrutiny. As scientists believe, zero gravity enables the glassy structure to form within a larger volume of the melt than would be the case on the Earth.

An important venue as regards the materials of construction for the future is the search for ways and means of drastically improving their strength. The problem of making metals more strong has been facing man since he first took a metal tool or weapon in his hands. The first success was scored when single metals gave way to alloys. When alloyed with tin, soft copper becomes strong bronze, and malleable iron fortified by carbon turns into mighty steel. Another method of improving strength, known since antiquity, is by heating and quenching a metal tool or weapon. Much later, man learned how to improve the strength of metals by what is known as strain or work hardening which modifies the metal's structure mechanically. All of these methods have been greatly improved since they were first invented, and are still being used. But they have proved inadequate in some applications.

When, in the middle of this century, space flight, the exploration of the oceans and seas, and the harnessing of nuclear power had all become urgent problems, the need arose for better materials, including those possessing superstrength. It was clear that fundamentally new ways and means of producing them should be looked for.

Shortly before that, physicists had calculated the maximum attainable strength of materials: the figure was found to be by an order of magnitude greater than the one actually achieved. Was it possible to come nearer to the theoretical limit of strength and how?

As often happens in science, the answer was found quite unexpectedly. Back in World War II American scientists had recorded quite a number of failures of electronic equipment and submarine telephone cables. It didn't take them long to pin-point the 'culprits': they were tiny crystals of tin or cadmium in the shape of needles or fibres (one or two microns in diameter) which would sometimes grow on the surface of tin- or cadmium-plated steel parts.

Before one could control the 'growth', or whiskers as they soon came to be called, one had to study them carefully. Laboratories in some countries set out growing whiskers from hundreds of metals and compounds, and investigating them thoroughly. It has finally been found (truly, every cloud has a silver lining) that they possess a tremendous strength close to its theoretical limit.

Whiskers owe their remarkable strength to their perfect structure which is in turn due to their minute size. The smaller a crystal, the less probable it is that it will contain any flaws, both internal and external. Even when highly polished, ordinary metals present, when suitably magnified, a surface which looks like a well ploughed field. In contrast, the crystalline fibres look practically smooth. (No signs of roughness have been found in some of them even at a magnification of forty thousand.) From a structural point of view, whiskers may well be likened to the ordinary cobweb which, in terms of the ratio of strength to weight or length, is the best performer among all materials, natural or man-made.

One application for the 'whiskers' (which have now come in 'vogue') is in composite materials or, simply, composites. In them the whiskers act as a reinforcement which carries the brunt of load. An early primitive composite is reinforced concrete which possesses one of the major characteristics of this class of materials: The steel rods embedded in the concrete give it more strength than the concrete itself. Back in Babylon, builders used cane to reinforce adobe houses. In ancient Greece, iron rods were used to fortify marble columns in palaces and temples. In the 16th century, the Russian architects Barma and Postnik used stone slabs reinforced with iron bars for their masterpiece, Basil the Blissful's Temple in Moscow, Russia.

Mechanical engineering, instrument-making, aerospace technology, power generation and other important industries, as we know them today, would hardly been able to exist without composites, a new class of high-strength, high-temperature, high-stiffness materials. As an American authority on the subject once noted, composites embody in a new form a very old and simple idea that the joint action of dissimilar materials produces an effect equal to that of a new material whose properties differ from those of its constituents both qualitatively and quantitatively.

Quite apart from a high ratio of strength, stiffness and heat resistance to weight or length, composites can be endowed with a package of special properties, such as the ability to absorb or transmit radio waves, to conduct electricity or to be magnetized with ease. This can be achieved by combining dissimilar materials, such as metals, alloys, ceramics, polymers, carbides, borides, and so on, in such a way that use is made of all the valuable properties of the constituents. Reinforcement can be supplied by fine metal wires: they are far cheaper to make than to grow whiskers. Again, wires can readily be woven into a kind of cloth or cage.

As Boris E. Paton believes, there is a bright outlook for multilayer or sandwich composites. Early examples of this class of materials are titanium-clad and aluminium-clad steels which have many years' record of service in industry.

Composites are playing an important role in aerospace technology. With them, an airplane or a spacecraft can cut their weight to a small fraction while gaining plenty in strength.

Of course, composites are still in their childhood. But even today, the demand for them exceeds their supply. The nearest future will see a continuous expansion in the field of application for composites, accompanied by a comparable increase in the range of materials that can be used as the reinforcement and as the matrix—the material in which the reinforcement is embedded.

Technology today needs many and diverse materials greatly outperforming their recent predecessors. Where machine designers would make do with simply strong steels yesterday, they need superstrong alloys today. Light-weight materials are giving way to superlight ones, plastic materials to superplastic, and hard materials to superhard. In their search for materials that would have the desired mechanical, physical and other properties, metal scientists can greatly be helped by the computer. Nobody is surprised today at the sight of a computer plotting the course to be flown by spacecraft, playing chess, writing verses, or translating from one language into another. Couldn't the computer be used to devise new alloys possessing some unique properties?

Exactly this task a team of researchers at the Baikov Institute of Metallurgy, USSR, set before themselves several years ago. The first thing they did was to develop a language in which instructions could be written for the computer. Then all the necessary data were written into the computer's memory, covering about fifteen hundred alloys, and the 'vital statistics' on all the metals: the electron structure of their atoms, melting points, lattice types, and other pertinent information. Thus informed, the computer was to predict what hitherto unknown alloys and compounds could be produced, to list their key properties and to suggest their applications.

Suppose that this task were to be tackled 'by hand', that is, by experiment. Then, each metal would have to be repeatedly alloyed with different amounts of some other metal chosen from some considerations, specimens would have to be prepared from the alloys thus produced, and each would have to be put to a host of physical and chemical tests. And what if the task weren't to study all likely combinations of just two metals but those of three, four, or five components, since state-of-the-art alloys are usually multicomponent systems? It would take tens or, perhaps, hundreds of years to do the job. Again, huge amounts of metals many of which are scarce and expensive would be needed for the experiments. Chances are that with some rare metals, such as rhenium or indium, all that the Earth has in its crust wouldn't be enough to meet the experimentors' demand.

In contrast, the computer works with digits, symbols, and equations, and it does its job at a far faster speed, doing millions of operations every minute.

As a result of their pains-taking effort, the team of researchers headed by Yevgeny M. Savitsky, a corresponding member of the Soviet Academy of Sciences, have been able first to predict, with the computer's aid, and then to produce many interesting materials. One of them is an unusually beautiful alloy of palladium and indium showing a lilac colour. But what counts more isn't of course the colour. More importantly, the new materials have excellent properties. The alloy of palladium and tungsten developed at the Institute has improved the reliability and service life of many electron devices more than twenty-fold.

It would hardly pay to use a computer in order to predict relatively simple alloys which can readily be obtained by mixing a small number of components. But it is really hard to manage without a computer where it comes to multicomponent compounds or alloys which are to stand up to enormous pressures and extremely high temperatures or which might have unpredictable properties. In fact, the computer has already 'prompted' around eight hundred new superconducting compounds and nearly a thousand alloys possessing special magnetic properties. Also, the computer has named as likely candidates about five thousand rare-earth compounds of which just one-fifth is known today. On top of that, the machine has tipped off the researchers about the transuranium elements.

One fact deserves special mention. The computer reported that an alloy of niobium and lead should display superconductivity. Soon the alloy was made in the laboratory although the scientists had argued for years that such an alloy could hardly be produced. The subsequent tests confirmed the rest of the computer's prediction.

A good deal of attention is being given to ultra-pure metals in which not more than one impurity atom is present for millions or even thousands of millions of atoms of the host material. Of course, purity is not an end in itself. The point is that many metals when they are practically free from any impurities behave differently from when they carry even the minutest traces of other elements.

One example is titanium, a very popular metal nowadays. It was quite recently, early in this century, that metal-makers weren't able to produce pure titanium—it would inevitably carry some impurities. Just a few tenths of one percent—but, as the Russian saying goes, one spoonful of tar is enough to spoil a caskful of honey. The impurities made titanium brittle, weak, and hardly machinable. Talk started that the metal was useless and good for nothing. Everything changed when high-purity titanium was first produced: it could be forged even at subzero temperature, it could be rolled into sheet, ribbon, wire, and even foil.

Today titanium is a major material of construction, figuring prominently in many fields of technology. Nature's supplies of titanium are truly inexhaustible, but it has to travel a long and circuitous path before it turns from ore to metal. Fortunately, this trouble is easy to shoot: the manufacture of titanium is being improved all the time, and the time is not far off when it will be as cheap as aluminium which was a serious rival for the noble metals in the 19th century.

And speaking of aluminium, it firmly ranks second solely to iron in the scale of production and the number of uses. Highly abundant in nature and possessing a package of valuable properties (such as light weight, resistance to corrosion, ductility, and high electrical conductivity), aluminium is being used in every industry, and its field of application is expanding all the time.

As we can see, iron faces now, towards the end of this century, quite a number of competing metals which have gone to work only recently. But metals aren't alone in their desire to oust iron: as vigilant are other rivals, such as polymers and ceramics, which have something to show for themselves in service. Yet, iron, despite its obviously 'pension' age (over five thousand years!), doesn't seem willing to go off the stage. As Academician Fersman wrote, "The future lies with other metals, and iron will eventually take up the position of an old, merited, but retired material. However, this future is still far away. Until then iron will remain the foundation of metallurgy, mechanical engineering, railways, shipbuilding, bridges, and transport".

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Venetsky S. I. *Tales about Metals.* Moscow, Mir Publishers, 1988 (in English)

Some of the Great Names in the History of Metallurgy

Anosov, Pavel Petrovich (1799-1851), a Russian metallurgist. Entered the St. Petersburg Mining Corps of Cadets at the age of 11. Graduated with honours in 1817 and was appointed to a minor post at the Zlatoust Crown Works. Promoted to Supervisor of the Zlatoust Arms Factory in 1819, to its Superintendent in 1824, and its Manager in 1829. From 1831 on, Mining Chief of the Zlatoust Works. From 1847 until his death, Chief of the Altai Works.

Anosov won world renown for his writings on the manufacture of iron and his re-discovery of the secret of damaskene lost in the Middle Ages. He explained the effect of the chemical composition, structure and treatment of steel on its properties. His findings formed the basis for the science of quality steels. Anosov summed up his studies in his now classical treatise, "On Damaskene" (1841), immediately translated into German and French.

Anosov was the first to use the microscope in studies into the structure of steel (1831), thus laying the foundation for the microscopic analysis of metals. He was behind the successful attempts (followed up by P. M. Obuhov) to make cast steel guns in the 1840s.

Anosov was elected a corresponding member of the Kazan University (1844) and an honorary member of the Kharkov University (1846).

Bardin, Ivan Pavlovich (1883-1960), a Soviet metallurgist, member of the USSR Academy of Sciences (1932), Hero of Socialist Labour (1945). Graduated from the Kiev Polytechnic Institute in 1910. Stayed in the USA as a worker in 1910-11. Worked at Russia's southern iron and steel works (Yuzovka, Yenakievo, etc.). One of the executives during the construction of the Kuznetsk Iron and Steel Works in 1929-1936. From 1937 on, in the top echelon of executives in Soviet ferrous metallurgy. Director of the Institute of Metallurgy (1939), and of the Central Research Institute of Ferrous Metallurgy (1944), named after him in 1960. Elected Vice President of the USSR Academy of Sciences in 1942.

During World War II Bardin headed the Academy's effort to tap the resources of the country's eastern regions for defence needs. This won him the State Prize in 1942. In 1949 he was awarded a second State Prize for the use of oxygen in the open-hearth process. In 1958 he was awarded the Lenin Prize for the first continuous steel casting machines.

Bessemer, Sir Henry (1813-1898), a British civil engineer and inventor, elected to the London Royal Society in 1879. Patented over a hundred inventions in various fields of technology. Those most important were the needle die for postal stamps and the word-casting machine in 1838, the sugar cane press in 1849, and the centrifugal pump in 1850. While werking on ways and means of improving the quality of a heavy artillery shell in 1854, he felt the need for a better steel-making process. In 1856 he patented a vessel for converting molten pig iron into steel at once by blowing a blast of air through the charge while in fusion until everything extraneous is expelled and only a definite quantity of carbon is left in combination. This process named after him revolutionized the iron and steel industry. In 1860, he patented a converter in which air is blown through the bottom and trunnions. He also advanced the idea of rolling steel without having to cast it into ingots.

Chernov, Dmitry Konstantinovich (1839-1921), a Russian metallurgist and metal scientist. Graduated from the St. Petersburg Practical Technological Institute in 1858. Worked at the Obuhov Steel Works in St. Petersburg in 1866-80. Professor of metallurgy at the Prince Mihail Artillery Academy from 1889 until his death.

In 1866-68 he found that the structure and properties of steel depend on the form of hot mechanical working and heat treatment it is given and discovered the critical points at which phase transformations occur in steel on heating and cooling and substantially change the structure and properties of the metal. In 1879 he came up with a theory explaining the solidification of the steel ingot (notably the formation and growth of crystals). These and other of Chernov's writings did much to transform metallurgy from an art into a science.

Chernov made valuable contributions to the converter process of steel-making and was among the first to stress the advisability of using an oxygen-enriched air to blow molten pig iron in the converter. He played with the idea of direct reduction of iron ore.

Chernov is among the fathers of present-day metal science and the founder of a major school of Russian metallurgists and metal scientists.

Cort, Henry (1740-1800), a British metallurgist. Took out a patent in 1783 for a mill to roll iron sheets and bars. Improved the puddling process in 1784 by hollowing out the bottom of the reverberatory furnace so as to contain the molten metal in this 'puddle'. Puddling played a great role in the development of the iron and steel industry in Britain during the Industrial Revolution.

Huntsman, Benjamin (1704-1776), a British metallurgist. Rediscovered around 1740 the crucible process of steel-making known to the ancients in India, Persia, Syria, and elsewhere but later lost to civilization. The crucible process produced strong steel for side arms, clockwork springs, and instruments.

Kurako, Mihail Konstantinovich (1872-1920), a Russian metallurgist. Went to work at the Alexander Iron and Steel Works in Ekaterinoslavl (now Dniepropetrovsk), then worked at other metallurgical plants in southern Russia. Was exiled to Russia's northern part for his participation in the 1905 revolution. Came back from the exile in 1908 to work as superintendent of the blast-furnace shop at the Hughes Iron and Steel Works. Founded a school of Russian blast-furnace specialists which contributed much to the progress of pig iron manufacture. Went to the Kuznetsk Basin in 1917 to head a major iron and steel project. Many of Kurako's ideas have been embodied in the Kuznetsk Iron and Steel Works.

Martin, Pierre (1824-1915), a French metallurgist. Graduated from a mining school and went to work at his father's iron and steel works at Fourchambot. Headed the iron and steel works at Civray (near Angoulême, France) between 1854 and 1883. Came up with a process for making cast steel in regenerative furnaces in 1864. Drawing upon the principle of heat regeneration developed shortly before by Friedrich Siemens of Germany, Martin used it to heat both air and fuel gas, thus achieving a temperature sufficient for steel making. Martin's open-hearth process came to be practised widely in the closing quarter of the 19th century.

Obuhov, Pavel Matveyevich (1820-1869), a Russian metallurgist. Graduated from the St. Petersburg Corps of Mining Engineers with honours in 1843. Was sent to work in the Urals. Was appointed Manager of the Zlatoust Arms Factory in 1854, where he completed his improvements of the crucible process. Was granted in 1857 the privilege of using his process for the large-scale production of high-quality cast steel. Designed in the late 1850s a factory to make steel field guns, which went into operation as the Prince Mihail Factory in 1860. This started the use of cast steel for gun barrels and was a turning point for Russian artillery. Obuhov's steel field gun which had fired over 4000 rounds without damage was awarded a gold medal at the World Exhibition in London in 1862. Elected a corresponding member of the Artillery Committee and appointed Chief of the Zlatoust Mining District in 1861. Headed the construction of a major steel works in St. Petersburg in 1863, later named after him.

Pavlov, Mihail Alexandrovich (1863-1958), a Soviet metallurgist; member of the USSR Academy of Sciences (elected in 1932); Hero of Socialist Labour (awarded in 1945). Graduated from the St. Petersburg Mining Institute in 1885 and took up the post of an engineer first at iron and steel works in the Vyatka Mining District, then, between 1896 and 1900, at the Sula Works. Began lecturing in 1900 at the Ekaterinoslavl Higher Mining School (now the Dniepropetrovsk Mining Institute). Later held the post of professor at the St. Petersburg (now Leningrad) Polytechnic Institute, the Moscow Mining Academy, and the Moscow Steel Institute.

Wrote many fundamental books on the theory and practice of the blast-furnace process and other metallurgical matters. Editor-in-Chief of the *Journal of the Russian Metallurgical Society* since its foundation and until his death. Took part in the designing of major iron and steel works, blast furnaces, and steel-making plant. Awarded the USSR State Prize for his activities in 1943 and 1947.

Thomas, Sidney Gilchrist (1850-1885), a British metallurgist. Educated at Dulwich college. Served as a clerk at the Court of

London and attended evening lectures at the Royal Mining School. While looking for ways and means of making steel from high-phosphorus pig iron in the Bessemer converter, he devised (with assistance from his cousin Peter Gilchrist) in 1878 what later became known as the Thomas-Gilchrist process in England or the Thomas process on the continent. Took out several patents covering the process between 1877 and 1882. Predicted that the high-phosphorus slag from his process could be used as a soil conditioner and stimulant to plant growth.

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S. Venetsky

Tales About Metals

For ages have metals been man's faithful servants in his endeavours to conquer the elements and penetrate into the secrets of Nature.

The world of metals is infinitely diverse and fascinating. The history of some of its representatives, and among them, copper, iron, lead, mercury, gold, silver, and tin, dates back thousands of years. Others were discovered just a few decades ago. The properties of metals are incredibly varied. Mercury will not freeze even at below-zero temperatures, while tungsten cannot be consumed by the hottest of flames. Lithium could make a fine swimmer, being only one half the weight of water and unable to sink no matter how hard it would try. Osmium is a heavy-weight champion of metals and, thrown into water, will hit the bottom as fast as a stone. Silver "delights" in conducting electricity, while titanium has an aversion for this pastime: its conductivity is only one three-hundredth of that of silver. We come across iron wherever we turn, and holmium is found in the earth's crust in such minute quantities that it is fabulously expensive. A grain of pure holmium is several hundred times more expensive than gold. But with all their differences, metals have one thing in common—they all belong to one large family. Venetsky's *Tales About Metals* describes the fate of many metals and their present and future uses. But it was not the author's idea to give any systematized information on the subject of metals. What he had in mind was mostly the amazing episodes, at times romantic or humorous, and at times tragic, in which the history of metals abounds. This book is for those who are ever curious, and not only for youngsters who are just discovering the world of science for themselves, those who, having said goodbye to school and college, still seize upon every opportunity to learn more about everything that surrounds them in life.

S. Venetsky

On Rare and Scattered Metals

Tales about Metals

As the title suggests, this popular-science book deals with the history of discoveries, the properties and uses of the most important rare and scattered metals. In it the reader will find fascinating information about treasure-troves being formed in our day, about a black notebook which witnessed a great scientific discovery, about an element which has vanished from the face of the earth like the once omnipotent dinosaur, about the role of some metals in criminalistics. The author hopes this book will be enjoyed by lay readers and specialists alike, by all who are interested in the history of metallurgy, chemistry, and the science of materials.

"Metallurgy in the 20th century bases itself on the latest advances in physics, chemistry, and physical chemistry. In turn, there are many spin-offs from metal-making: progress in these and, indeed, any other sciences would have been impossible without the various materials possessing a broad gamut of truly amazing properties, and these materials come from metallurgy, one of the most ancient, the most advanced, and the most promising of man's arts."

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